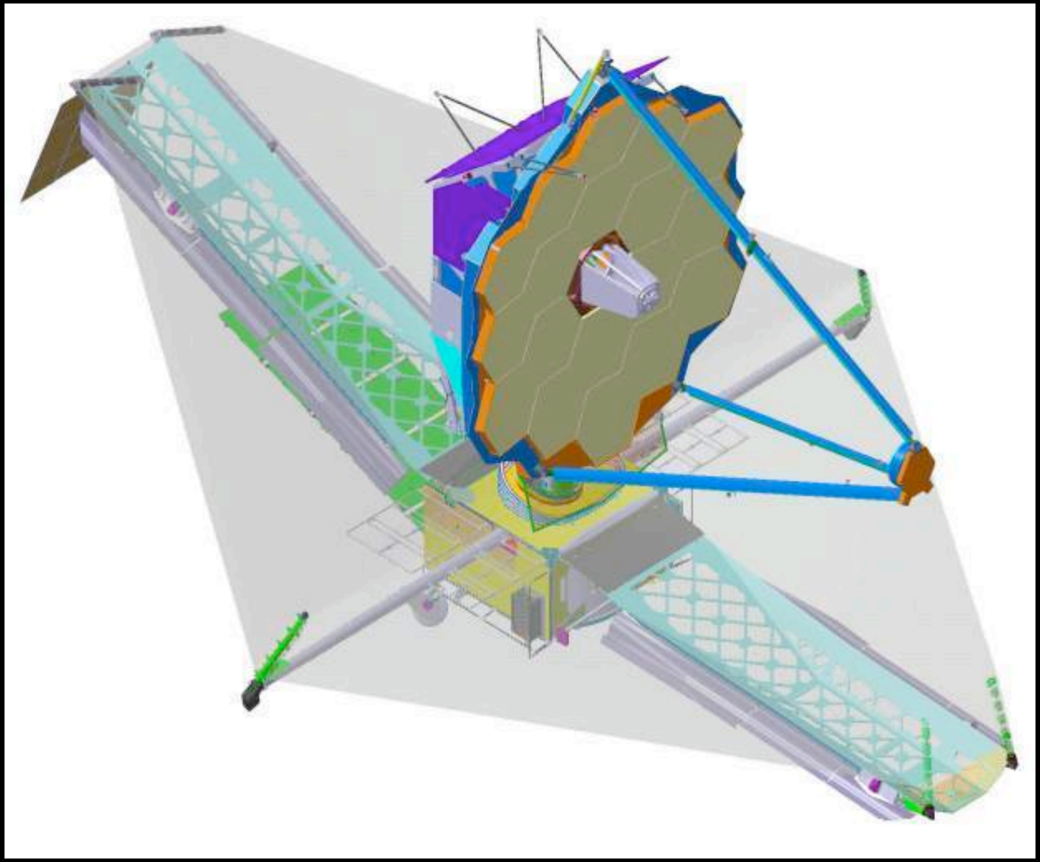
Exoplanets with the James Webb Space Telescope

John Mather, NASA's GSFC

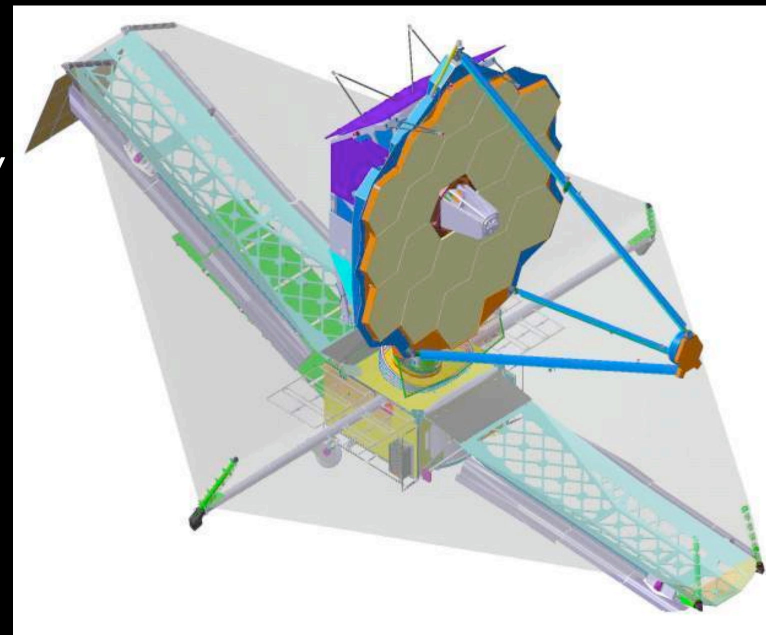
January 10, 2009



JWST Mission "At a Glance"

Organization

- Mission Lead: Goddard Space Flight Center
- International collaboration with ESA & CSA
- Prime Contractor: Northrop Grumman Space Technology
- Instruments:
  - Near Infrared Camera (NIRCam) – Univ. of Arizona
  - Near Infrared Spectrograph (NIRSpec) – ESA
  - Mid-Infrared Instrument (MIRI) – JPL/ESA
  - Fine Guidance Sensor (FGS) – CSA
- Operations: Space Telescope Science Institute



Description

- Deployable infrared telescope with 6.5 meter diameter segmented adjustable primary mirror
- Cryogenic temperature telescope and instruments for infrared performance
- Launch 2013 on an ESA-supplied Ariane 5 rocket to Sun-Earth L2
- 5-year science mission (10-year goal)

www.JWST.nasa.gov

JWST Science Themes

End of the dark ages: First light and reionization

The assembly of galaxies

Birth of stars and proto-planetary systems

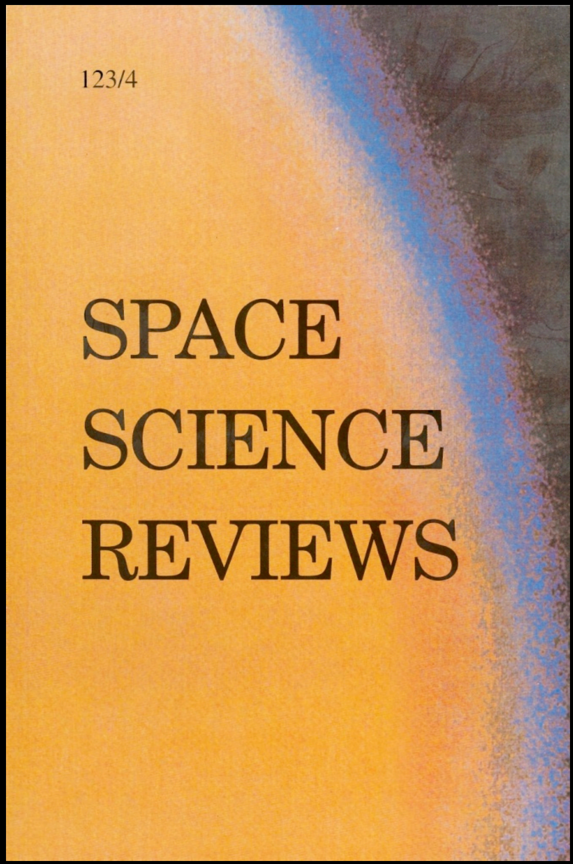
Planetary systems and the origin of life

JWST Science Working Group (#4)

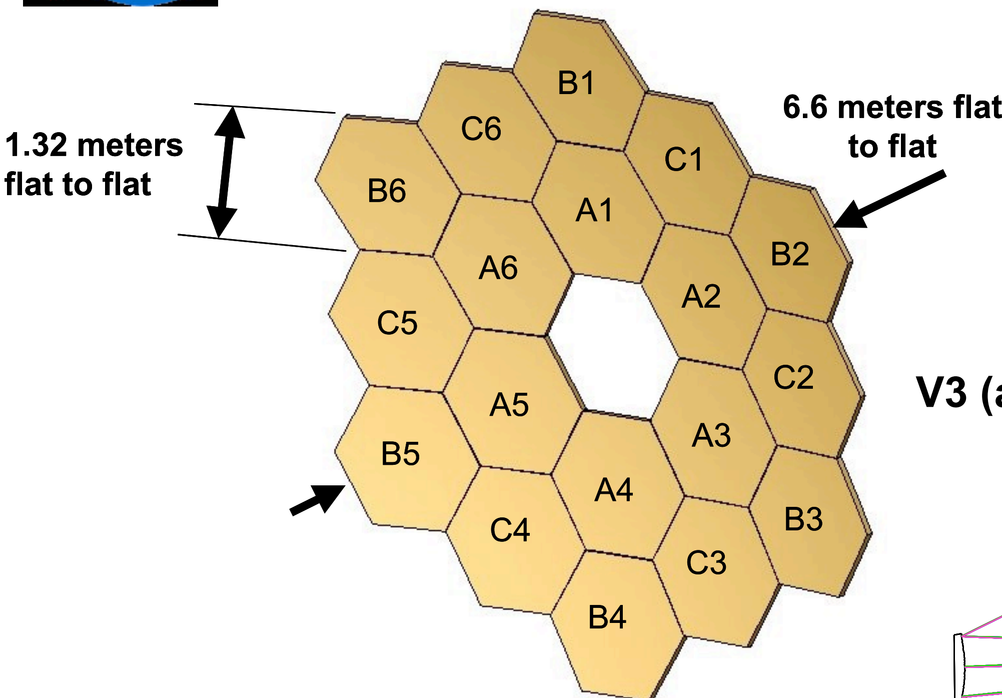
- 6 Interdisciplinary Scientists: H. Hammel, S. Lilly, J. Lunine, M. McCaughrean, M. Stiavelli, R. Windhorst
- Instrument Team Lead/ Science Representative: M. Rieke (NIRCam), G. Rieke and G. Wright (MIRI), Rene Doyon (FGS), & rotating scientist member, NIRSpec
- Telescope Scientist: M. Mountain (also STScI Director)
- Ex Officio: J. Mather (Chair), J. Gardner, M. Clampin, M. Greenhouse, K. Flanagan, G. Sonneborn, P. Jakobsen, J. Hutchings

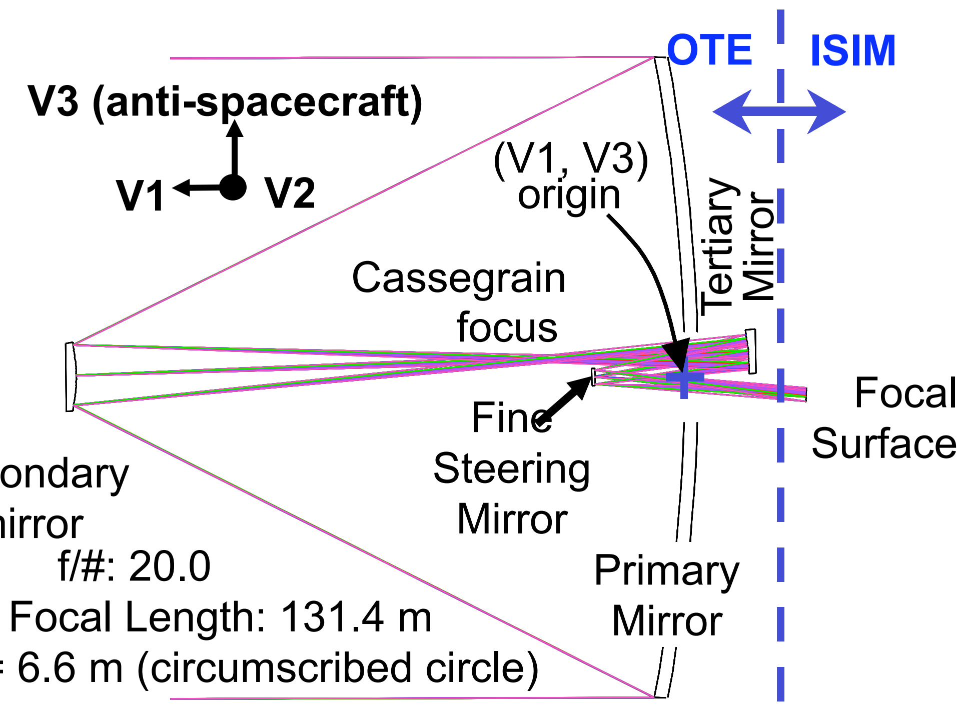
Project Summary Document

- Gardner et al. 2006, Space Science Reviews, 123/4, 485 http://jwst.gsfc.nasa.gov/scientists.html



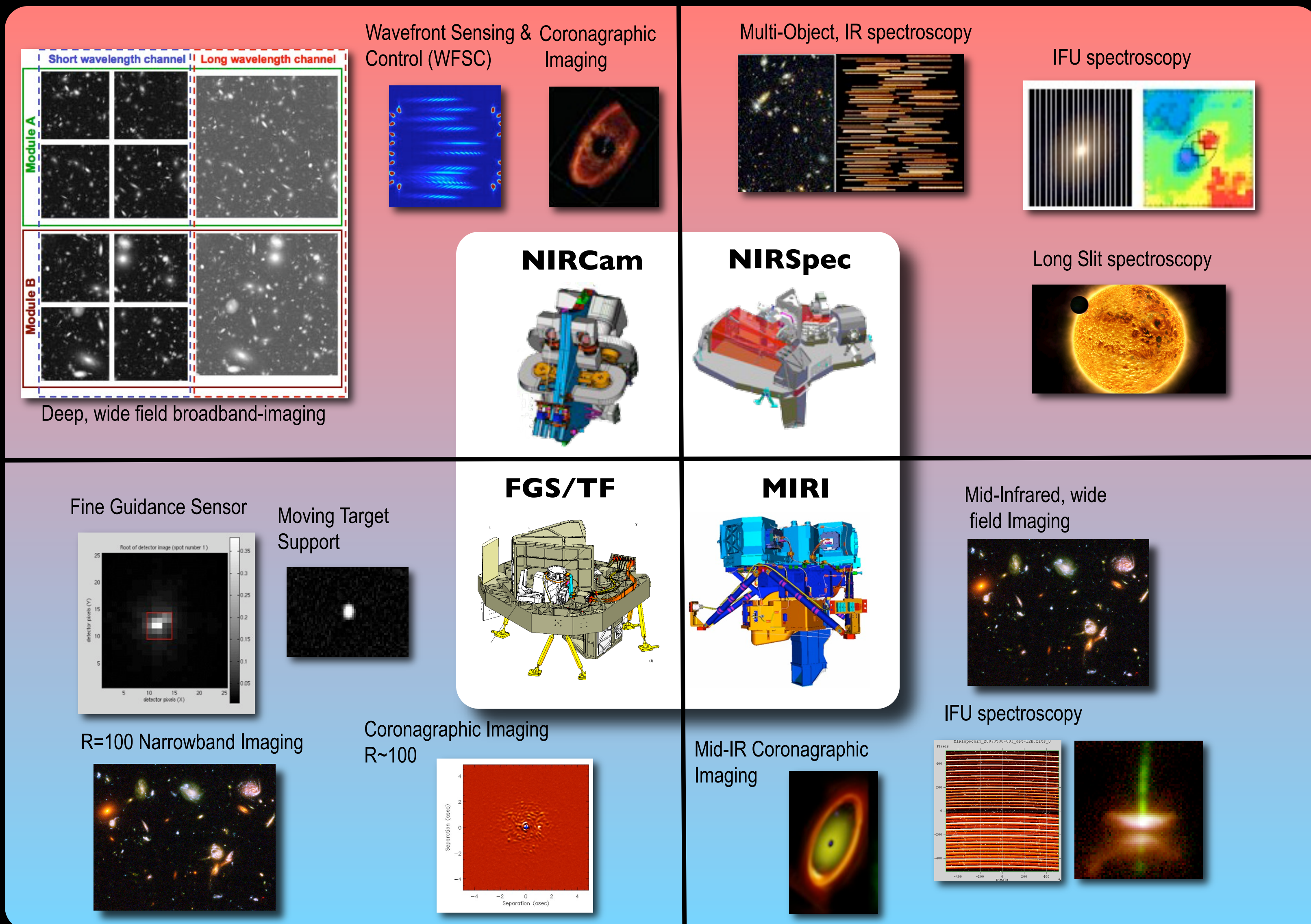
Three Mirror Anastigmat Optical Design Provides a Wide Field-of-View



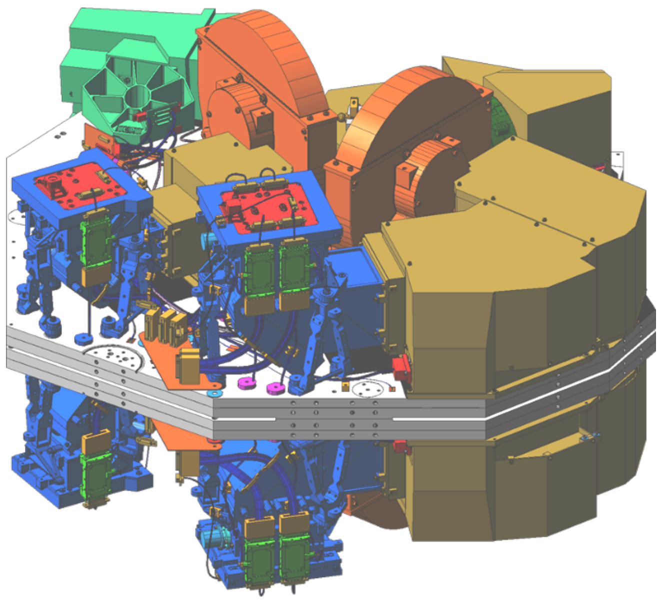


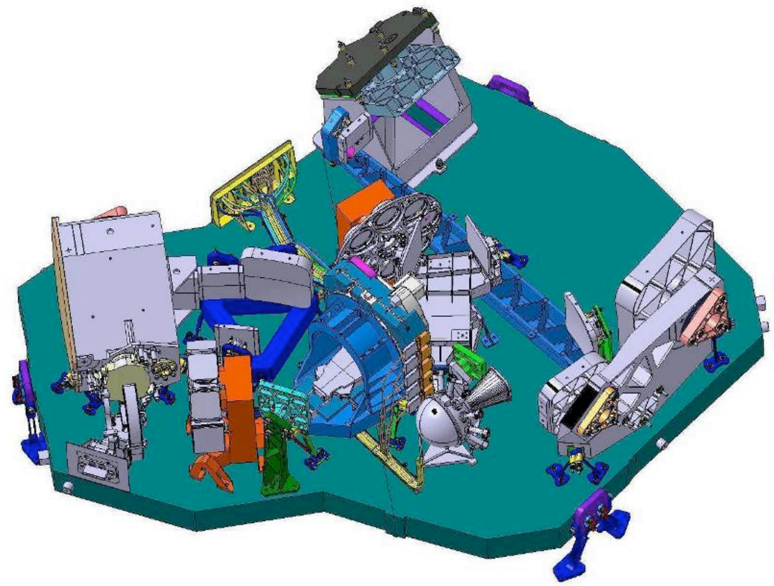
f/#: 20.0
Effective Focal Length: 131.4 m
PM diameter = 6.6 m (circumscribed circle)

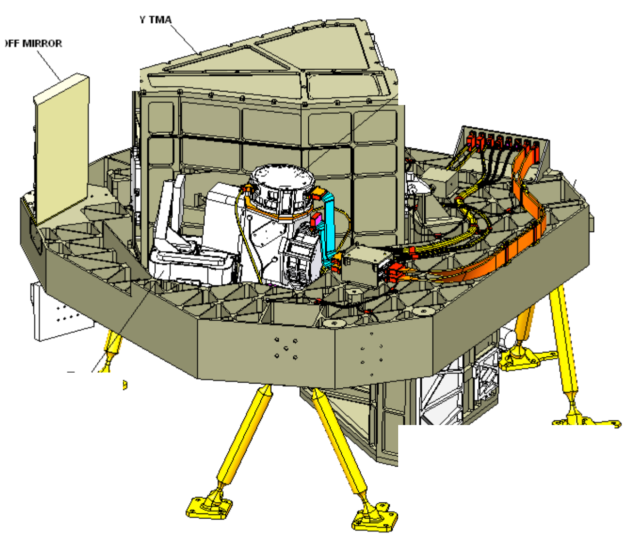
JWST Instruments

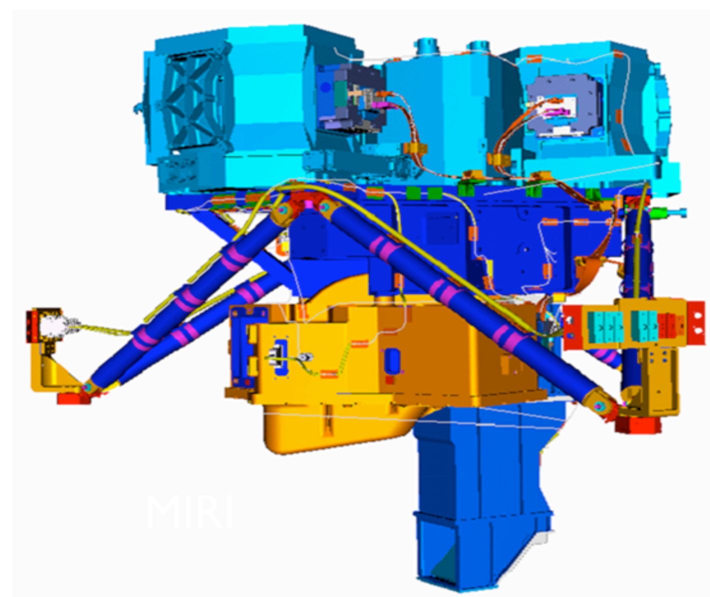


Four science instruments enable imagery and spectroscopy over the 0.6 – 29 micron spectrum

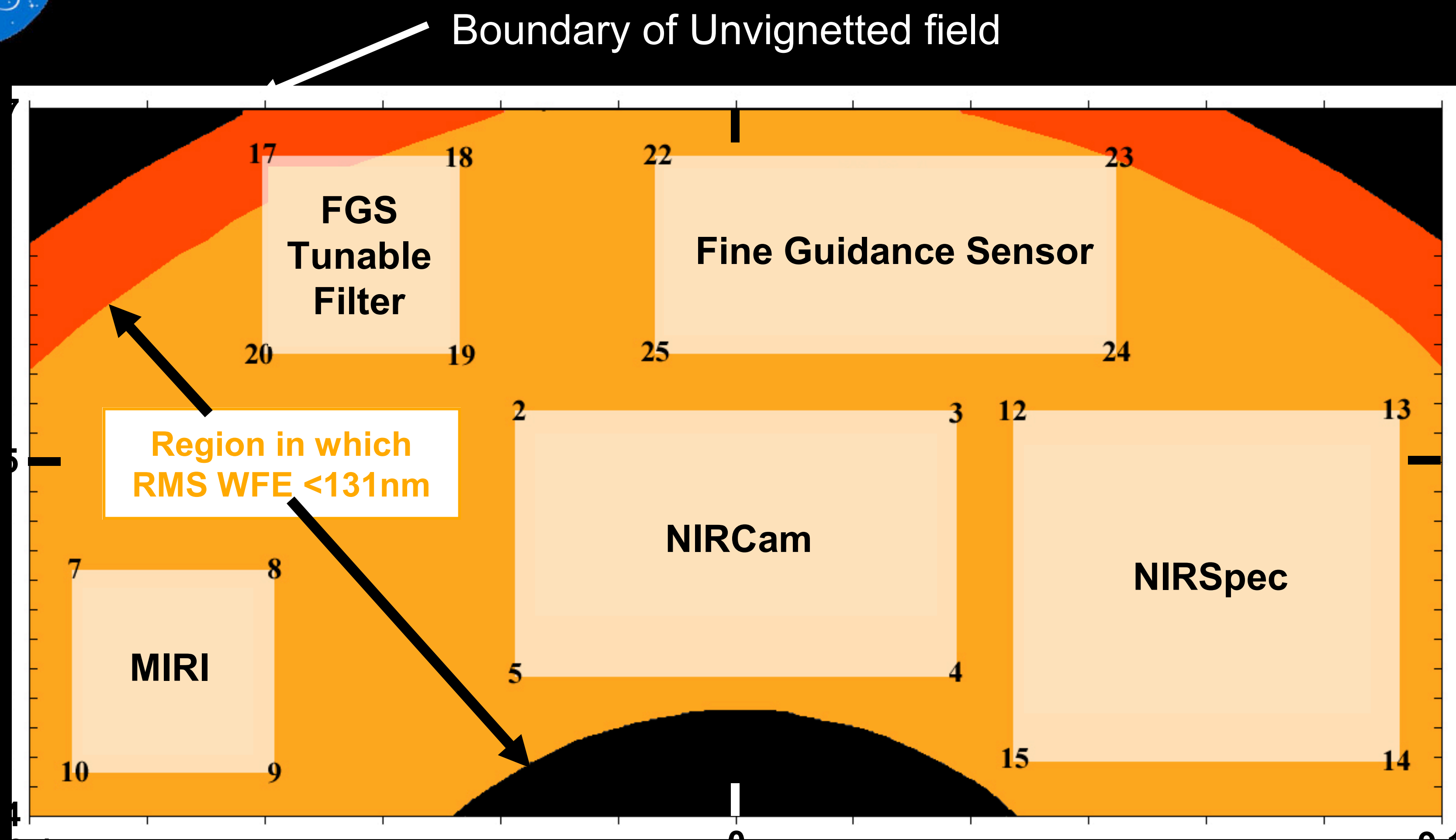








Field Position of Science Instruments



Instruments and Guidance Sensor Share Telescope Field of View

Sensitivity & Resolution

- Cameras and R ~ 100 spectroscopy background limited at all wavelengths
  - 6.5 m mirror much larger than HST, Spitzer - big gains
  - Background dominated by zodi light, and at > 12 μm from thermal emission from sunshield
  - Other stray light from galaxy, sometimes Earth or Moon
- NIRSpec sensitivity detector limited at R ~ 1000
- Image quality
  - Diffraction limited (λ/14 rms wavefront) at 2 μm (~ ground AO)
  - 0.034 arcsec pixels in NIRCam short band (Nyquist @ 2 μm)
  - 0.068 arcsec in NIRCam long band and Fine Guider
  - 0.2 x 0.45 arcsec shutters for NIRSpec
  - 0.11 arcsec pixels for MIRI camera
  - 0.19 - 0.28 arcsec pixels for MIRI image slicer integral field unit

TABLE IX

Science instrument characteristics

Instrument	Wavelength(μm)	Detector	Plate scale (milliarcsec/pixel)	Field of view
NIRCam			32	2.2×4.4 arcmin
Short	0.6–2.3	Eight 2048×2048		
Long[a]	2.4–5.0 2048×2048	Two	65	2.2×4.4 arcmin
NIRSpec	0.6–5.0	Two	100	
MSA[b]			2048×2048	3.4×3.1 arcmin
Slits[c]				$\sim 0.2 \times 4$ arcsec
IFU				3.0×3.0 arcsec
MIRI	5.0–29.0	1024×1024	110	
Imaging				1.4×1.9 arcmin
Coronagraphy				26×26 arcsec
Spectra[d]	5.0–10.0			0.2×5 arcsec
IFU	5.0–29.0	Two 1024×1024	200 to 470	3.6×3.6 to 7.5×7.5 arcsec
TFI	1.6–4.9[e]	2048×2048	65	2.2×2.2 arcmin

[b]NIRSpec includes a microshutter assembly (MSA) with four 365×171 microshutter arrays. The individual shutters are each 203 (spectral) $\times$ 463 (spatial) milliarcsec clear aperture on a 267×528 milliarcsec pitch.

JWST Sensitivities

TABLE X

Instrument sensitivities

Instrument/mode	λ (μm)	Bandwidth	Sensitivity
NIRCam	2.0	$R = 4$	11.4 nJy, AB = 28.8
TFI	3.5	$R = 100$	126 nJy, AB = 26.1
NIRSpec/Low Res.	3.0	$R = 100$	132 nJy, AB = 26.1
NIRspec/Med. Res.	2.0	$R = 1000$	1.64×10^{-18} erg s^{-1} cm^{-2}
MIRI/Broadband	10.0	$R = 5$	700 nJy, AB = 24.3
MIRI/Broadband	21.0	$R = 4.2$	8.7 μJy, AB = 21.6
MIRI/Spect.	9.2	$R = 2400$	1.0×10^{-17} erg s^{-1} cm^{-2}
MIRI/Spect.	22.5	$R = 1200$	5.6×10^{-17} erg s^{-1} cm^{-2}

Note. Sensitivity is defined to be the brightness of a point source detected at 10σ in 10,000 s. Longer or shorter exposures are expected to scale approximately as the square root of the exposure time. Targets at the North Ecliptic Pole are assumed. The sensitivities in this table represent the best estimate at the time of submission and are subject to change.

Observing the "First" Light

TABLE II

JWST measurements for the end of the dark ages theme

Observation	Instrument	Depth, Mode	Target
Ultra-deep survey (UDS)	NIRCam	1.4 nJy at 2 μm	10 arcmin^2
In-depth study	NIRSpec	23 nJy, $R \sim 100$	Galaxies in UDS area
	MIRI	23 nJy at 5.6 μm	Galaxies in UDS area
Lyman α forest diagnostics	NIRSpec	2×10^{-19} erg cm^{-2} s^{-1}, $R \sim 1000$	Bright $z > 7$ quasar or galaxy
Survey for Lyman α sources	TFI	2×10^{-19} erg cm^{-2} s^{-1}, $R \sim 100$	4 arcmin^2 containing known high-z object
Transition in Lyman α/Balmer	NIRSpec	2×10^{-19} erg cm^{-2} s^{-1}, $R \sim 1000$	UDS or wider survey area
Measure ionizing continuum	NIRSpec	2×10^{-19} erg cm $^{-2}$ s^{-1}, $R \sim 1000$	Same data as above
Ionization source nature	NIRSpec	2×10^{-19} erg cm^{-2} s^{-1}, $R \sim 1000$	Same data as above
	MIRI	23 nJy at 5.6 μm	
LF of dwarf galaxies	NIRCam	1.4 nJy at 2 μm	UDS data

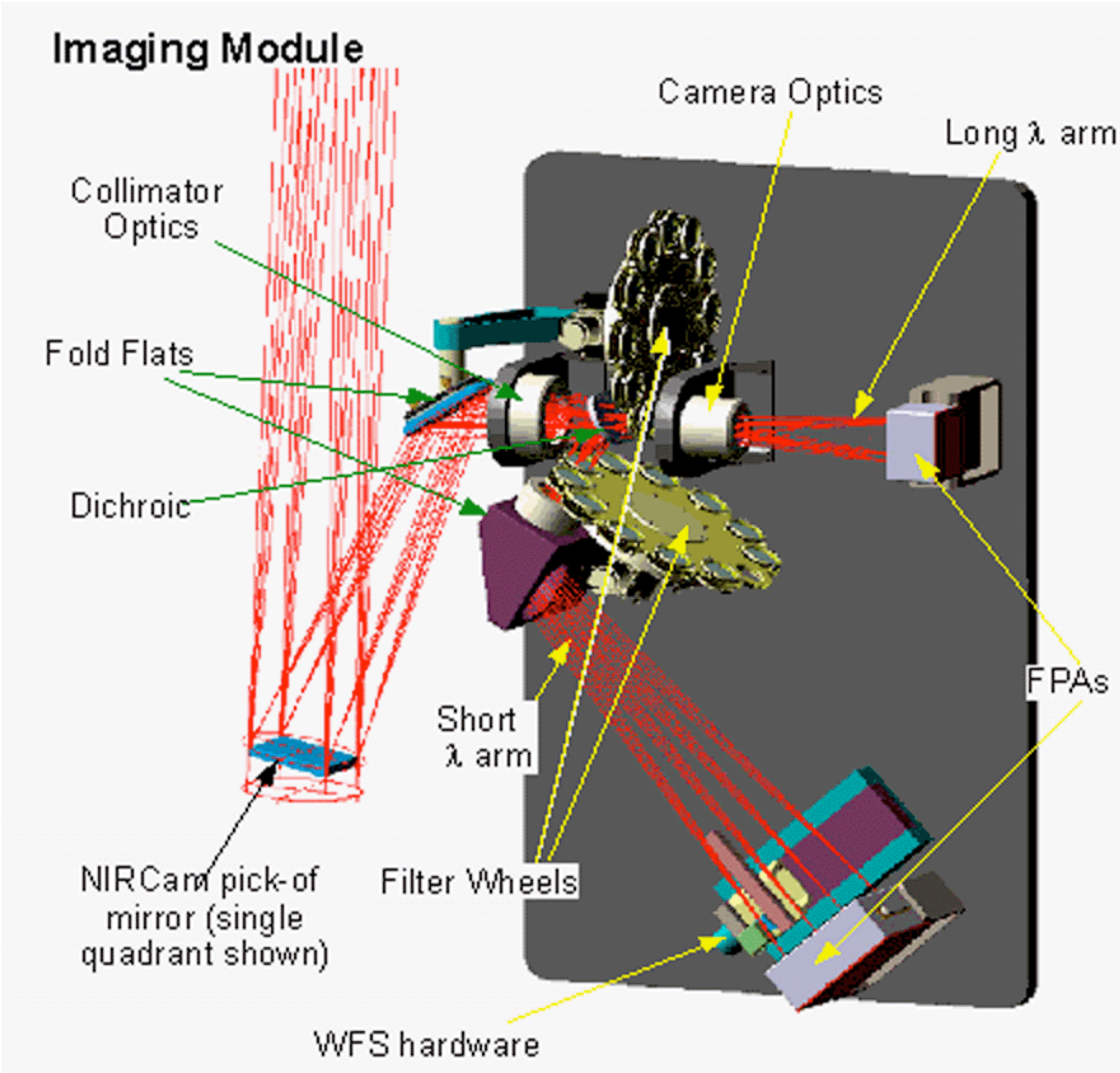
Assembly of Galaxies

TABLE III

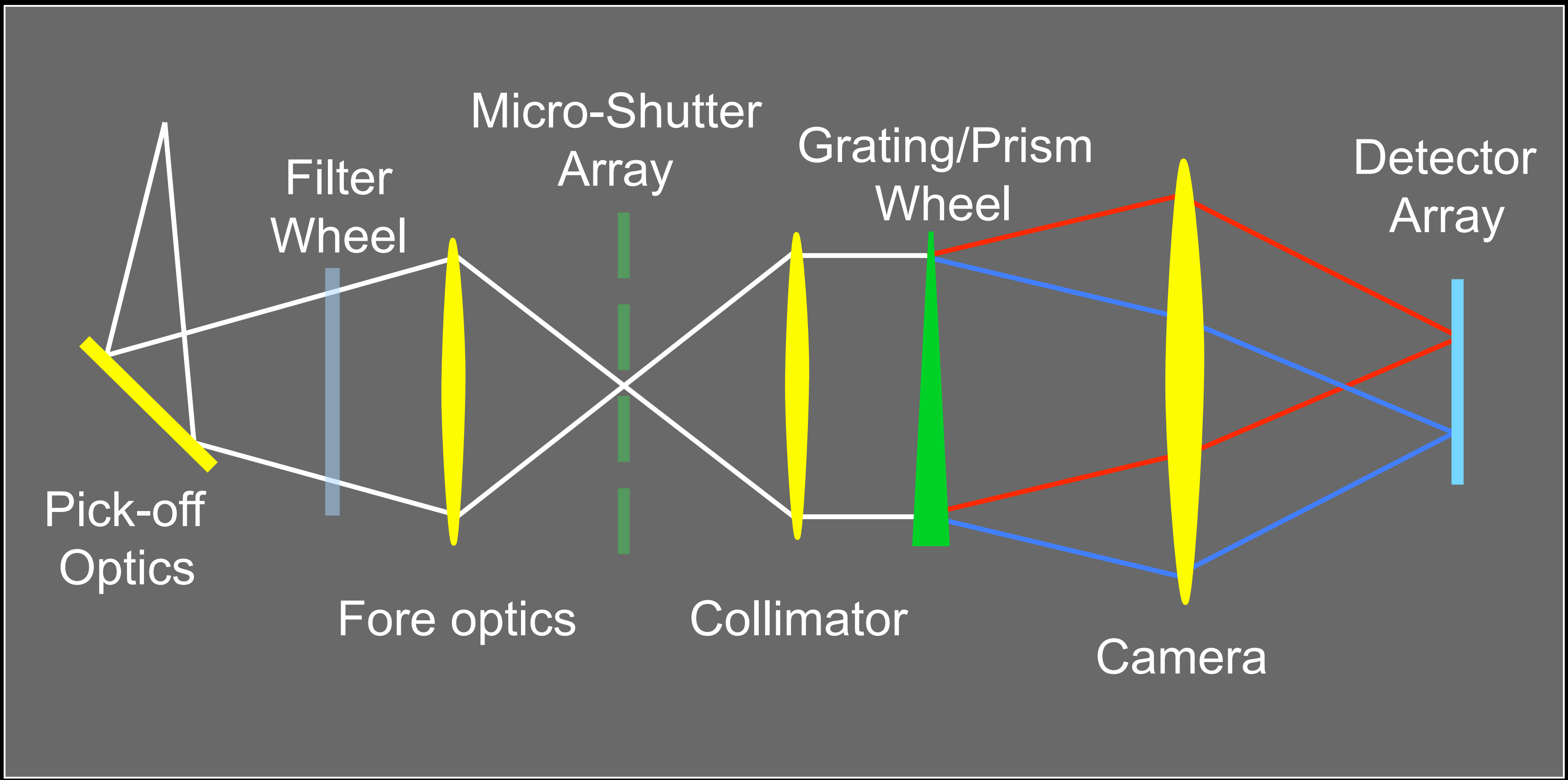
JWST measurements for the assembly of galaxies theme

Observation	Instrument	Depth, Mode	Target
Deep-wide survey (DWS)	NIRCam	3 nJy at 3.5 μm	100 arcmin^2
Metallicity determination	NIRSpec	5×10^{-19} erg s^{-1}cm^{-2}, $R\sim1000$	Galaxies in DWS
Scaling relations	MIRI	11 μJy at 9 μm, $R\sim3000$	Lyman Break galaxies at $z\sim3$
	NIRCam	3 nJy at 3.5 μm	DWS data
Obscured galaxies	MIRI	23 nJy at 5.6 μm	ULIRGs
	NIRSpec	5×10^{-19} erg s^{-1} cm^{-2}, $R\sim1000$	ULIRGs and AGN
	MIRI	1.4×10^{-16} erg s^{-1}cm^{-2} at 24μm, $R\sim2000$	ULIRGs and AGN

A NIRCam Imaging Module

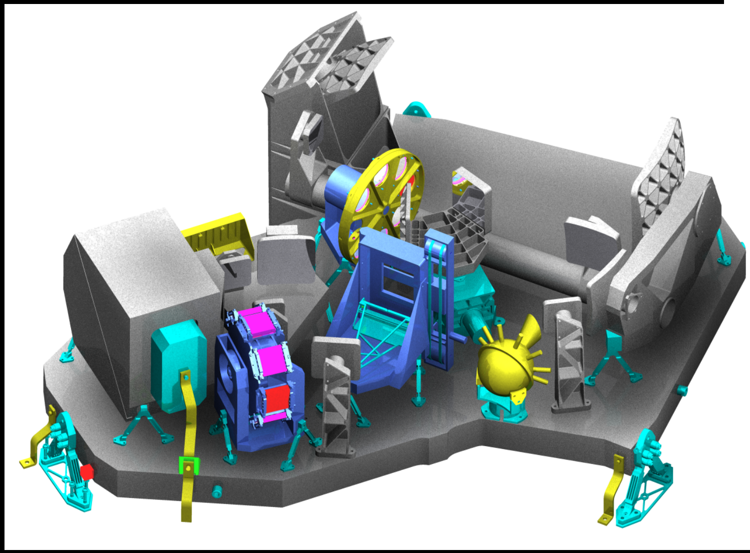


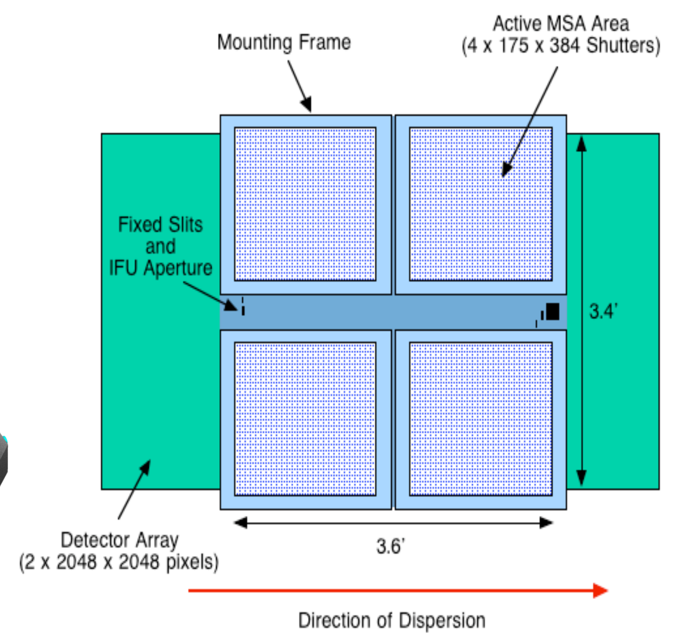
NIRSpec Schematic



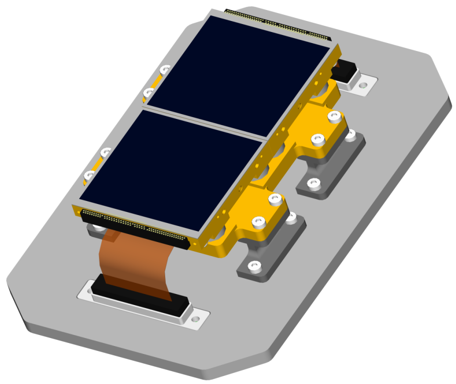
NIRSpec: ESA & Astrium

- > 100 Objects Simultaneously
- 9 square arcminute FOV



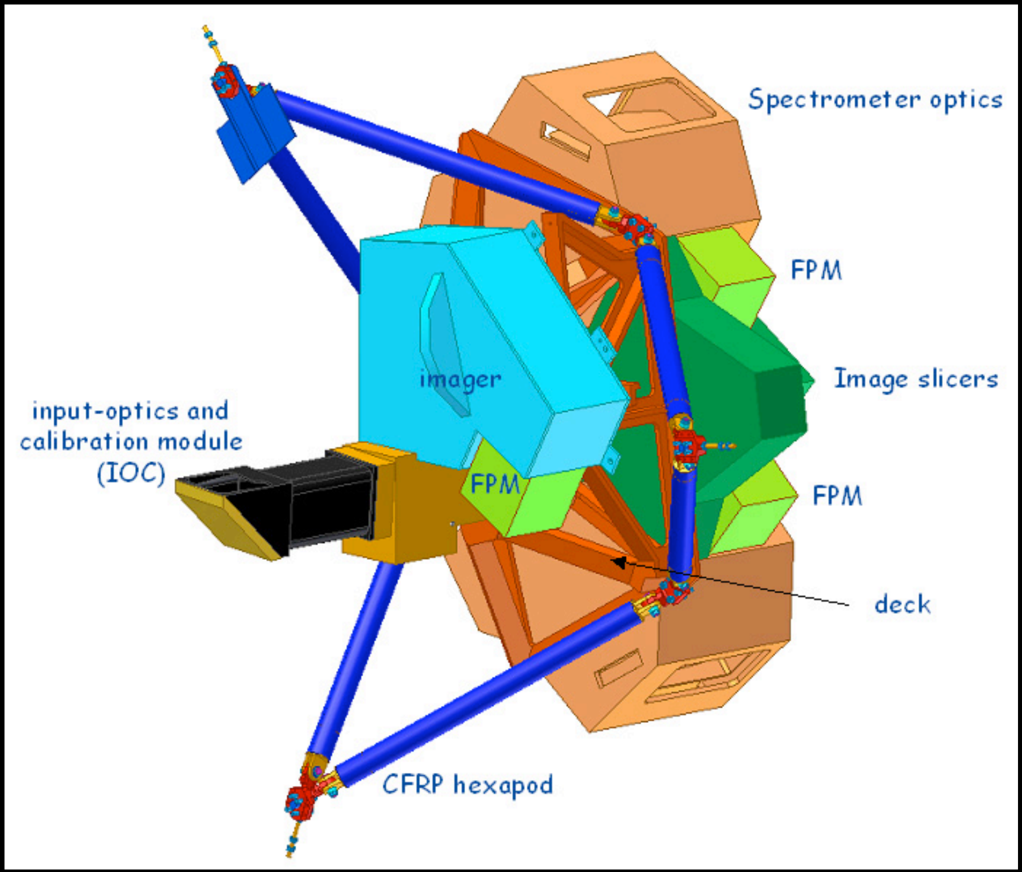


- **Implementation:**
  - 3.5' Large FOV Imaging Spectrograph
  - 4 x 175 x 384 element Micro-Shutter Array
  - 2 x 2k x 2k Detector Array
  - Fixed slits and IFU for backup, contrast
  - SiC optical bench & optics



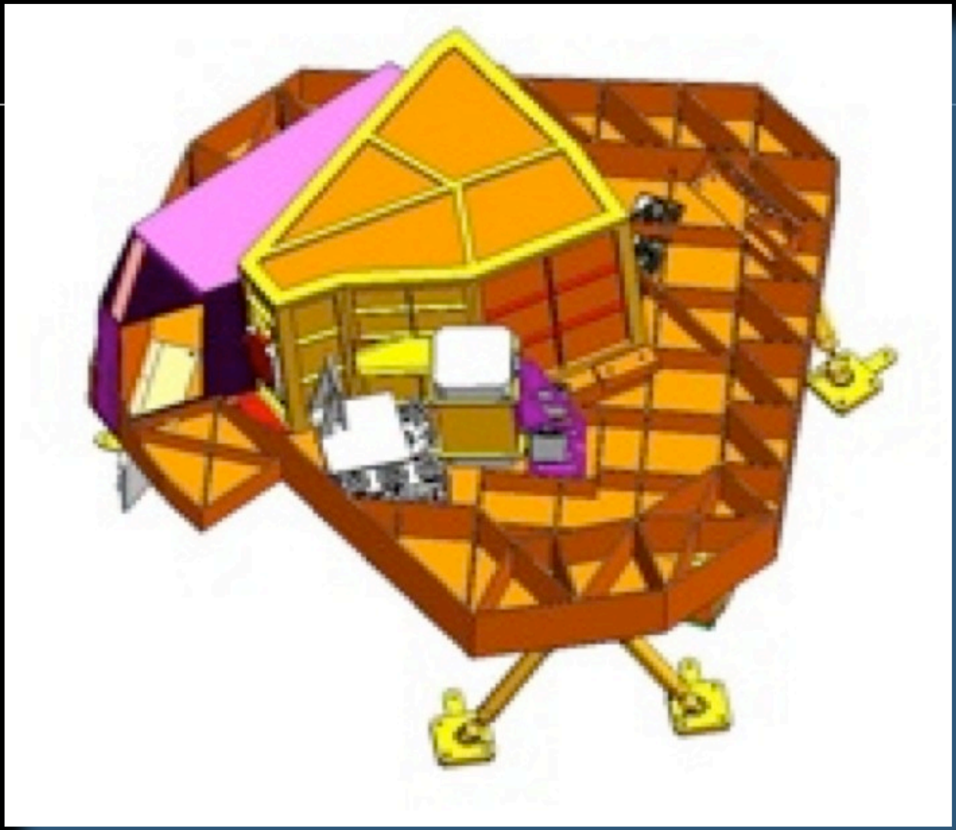
Mid-Infrared Instrument (MIRI)

- Science team G. Rieke (lead), G.Wright (co-lead)
- European Consortium sponsored by ESA in partnership with NASA/JPL
- Science Goals include
  - Search for the origins of galaxies
  - Birth of stars and planets
  - Evolution of planetary systems
- Imaging
  - λ=5-29 µm wavelength range
  - Diffraction limited imaging with 0.1” pixels
  - ~1.7’ field of view
  - Able to image sources as bright as 4 mJy at λ=10µm
  - ≥12 bandpass filters
  - Low resolution spectrograph (R~100; λ=5-10 µm) for single, compact sources
  - Simple coronagraph
- Spectroscopy
  - λ=5-29 µm wavelength range, reach λ= 28.3 µm
  - Integral field spectroscopy with > 3” field of view
  - R~2000-3700 from λ=5-29 µm



Optics Module concept developed by European Consortium

Fine Guidance Sensor (FGS)



- Guide star availability with >95% probability at any point in the sky
- Wide open bandpass for guiding (0.5 µm - 5.0 µm)
- Includes Tunable Filter Imager with R = 70 - 150, 1.7 µm - 4.8 µm
- Coronagraph

2008 Progress

- General
  - JWST successfully completed Non-Advocate Review and Confirmation Review and is approved to begin Implementation Phase
  - All observatory components, except for the spacecraft and membrane management system of the sunshield, have successfully completed their preliminary design reviews
  - All science instruments successfully completed critical design reviews
  - HQ approved moving object tracking requirement
- Telescope and Mirrors
  - All flight primary, secondary and tertiary mirrors completed machining and are in stages of rough polishing, smooth out and figure grinding
  - Mirror “Manufacturing Percentage” progressed from 41% to 55%
- Observatory
  - Sunshield Preliminary Design Review held in February 2008
  - Observatory Integration & Test control room opened at NGST
- Ground Segment
  - Delivered all Science Instrument Integrated Test Sets (SITSs) and Science Instrument Development Units (SIDUs) to SI teams in the US, Canada and Europe

2008 Progress continued

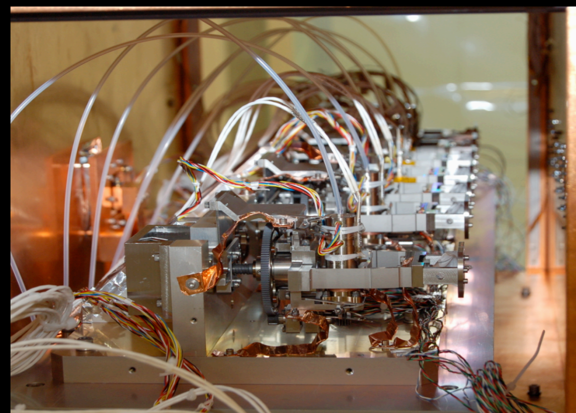
- Integrated Science Instrument Module (ISIM)
  - MIRI
    - MIRI Verification Model (VM) completed, tested and achieved 6.2K operating temperature and first light!
    - Selected flight detectors for MIRI
  - NIRSpec
    - Delivered Engineering Test Unit detector subsystem to Astrium
    - Selection of flight detectors agreed to by NASA & ESA
    - ESA approved larger (1.6 arcsec square) aperture for NIRSpec for transits
  - NIRCam
    - Selected ALL flight detectors and filters for NIRCam
    - Completed bonding and vibration testing of the NIRCam ETU Optical Bench
  - FGS
    - Held FGS System CDR at COM DEV
    - Engineering Test Unit assembly begun, tunable filter etalon tested at cryo
    - CSA added Non-Redundant Masking to their Tunable Filter Imager
  - Structure
    - Completed bonding 5 of 13 Flight Hardware Decks

Primary Mirror Segment Assembly Flight Hardware Production Well Underway

Launch Restraint Flexures

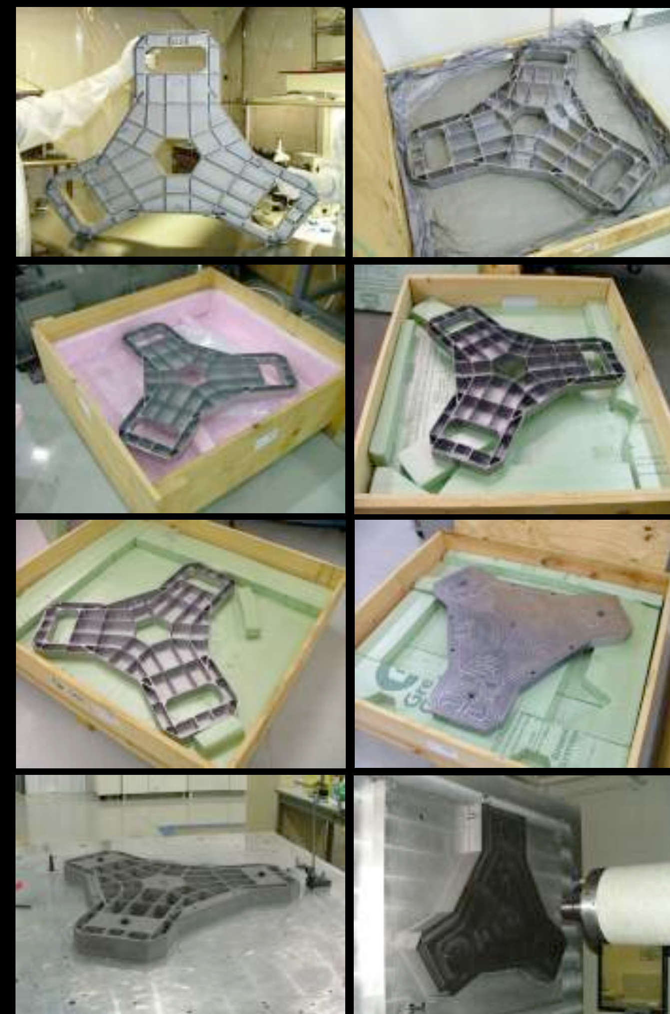
PM Bipod Mounting Brackets

Strongback Struts



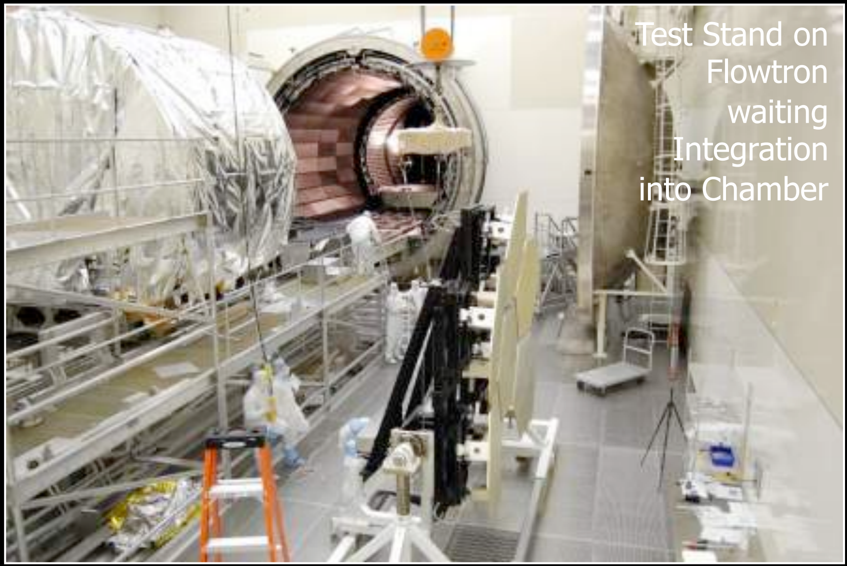
Flight actuators under test

PM Whiffle Assemblies



PM Delta Frames 1-8

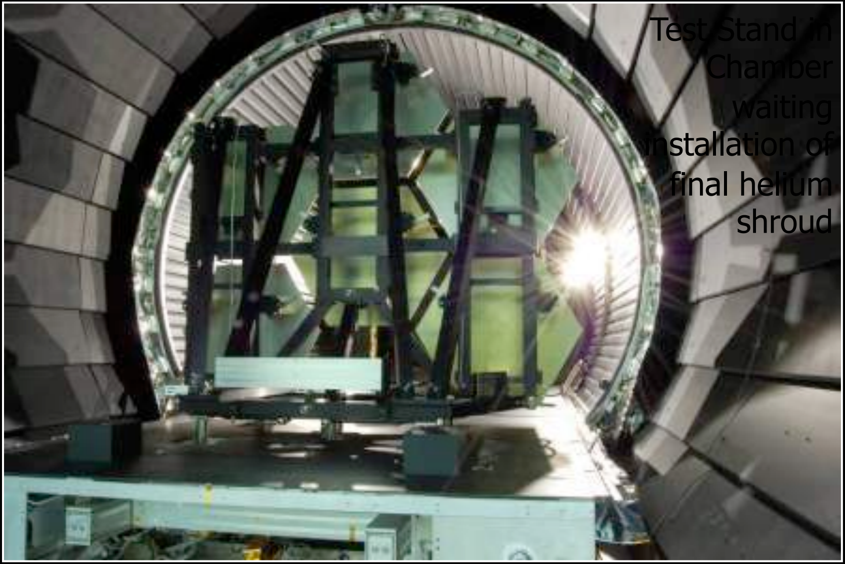
Installation of Test Stand with Mass Simulators into MSFC XRCF Test Chamber Complete



Test Stand on Flowtron waiting Integration into Chamber

Craning Test Stand in Place

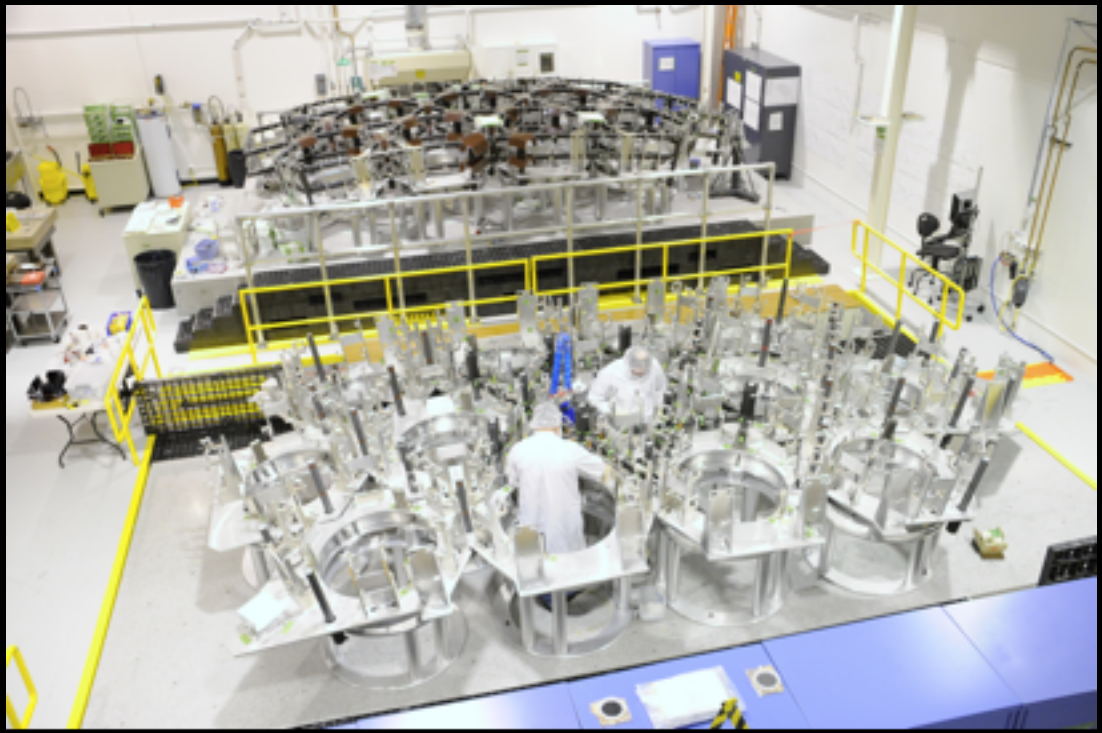
Installing Test Stand into Chamber

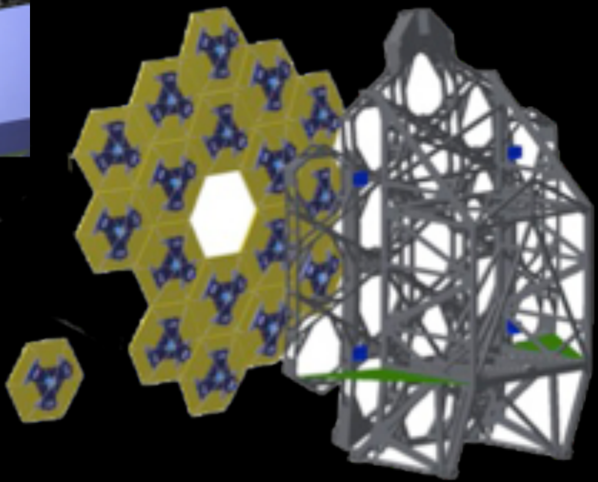


Test Stand in Chamber waiting Installation of final helium shroud

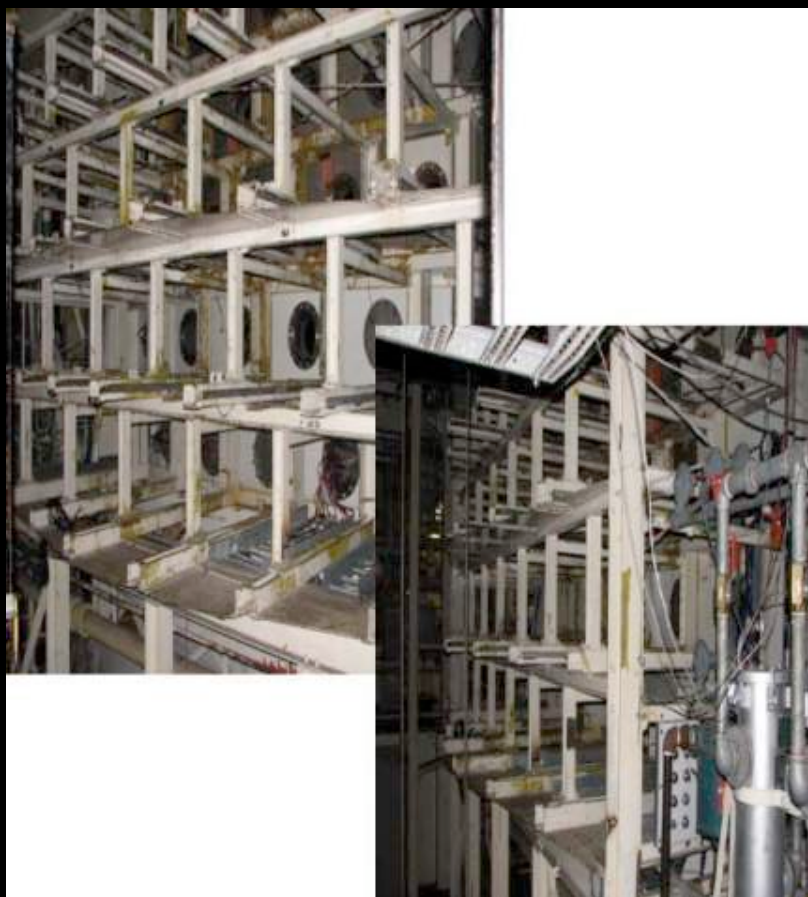
A1 and EDU at the XRCF

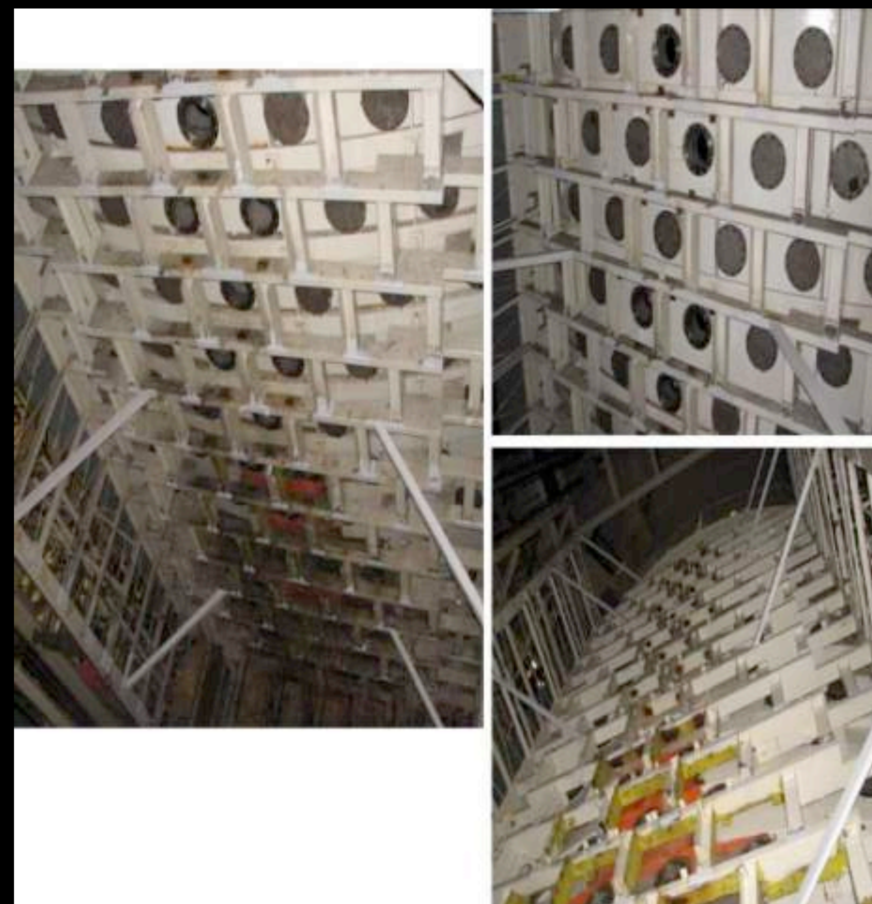
Flight Backplane Started





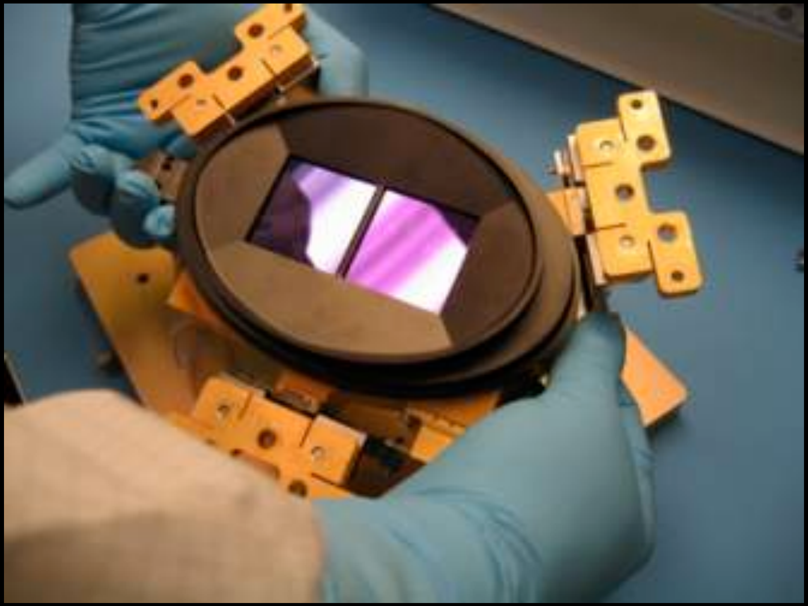
JSC Chamber A Modification Progress





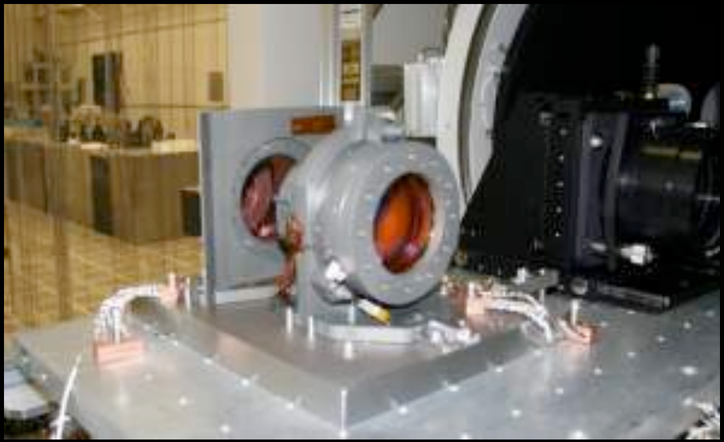
External chamber modifications – removal of solar simulator structures

ETU Hardware Queuing Up for Instrument I&T



NIRSpec Focal Plane Assembly

NIRCam Pupil Imaging Lens Mechanism

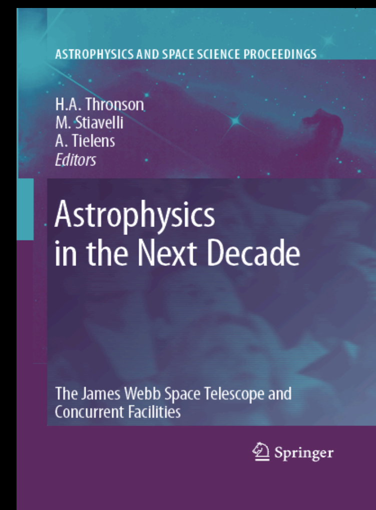


NIRCam Shortwave Camera Triplet & Beamsplitter

NIRSpec Fore Optics

2009 Major Events

- Sunshield Membrane Management System Preliminary Design Review, February
- ISIM Critical Design Review, March
- Assembly & Testing of NIRCam Engineering Test Unit, June
- Observatory Flight Software Build 1 Critical Design, June
- Microshutter device delivered from GSFC to NIRSpec, June
- NIRCam Flight Instrument build commences, August
- Electro-optical tests of ETU FGS at operating conditions, October
- Mission Critical Design Review scheduled for December
- MIRI Flight Instrument testing commences



2007 Tucson conference proceedings out soon

JWST Project seeking Associate Project Scientist for Integration and Test
See AAS job bulletin position 25420

The James Webb Space Telescope Capabilities for Astrobiology

Mark Clampin
JWST Observatory Project Scientist
Goddard Space Flight Center

contributors: Jonathan Lunine, George Rieke, Don Lindler (GSFC), Eliza Miller-Ricci (CfA), Sara Seager (MIT), Tom Greene (NASA/Ames), Drake Deming (GSFC), and JWST SWG and SI Teams

The NASA Astrobiology Roadmap

- Goal 1 — Understand the nature and distribution of habitable environments in the universe. Determine the potential for habitable planets beyond the Solar System, and characterize those that are observable.

- GOAL 7 — Determine how to recognize signatures of life on other worlds and on early Earth. Identify biosignatures that can reveal and characterize past or present life in ancient samples from Earth, extraterrestrial samples measured in situ or returned to Earth, and remotely measured planetary atmospheres and surfaces. Identify biosignatures of distant technologies.

Documentation

- Astrobiology Whitepaper: Lunine & Seager
  - (Google "jwst white paper")
- JWST Coronography Whitepaper
- JWST Transit Science Whitepaper
- Space Science Reviews

Astrobiology Themes

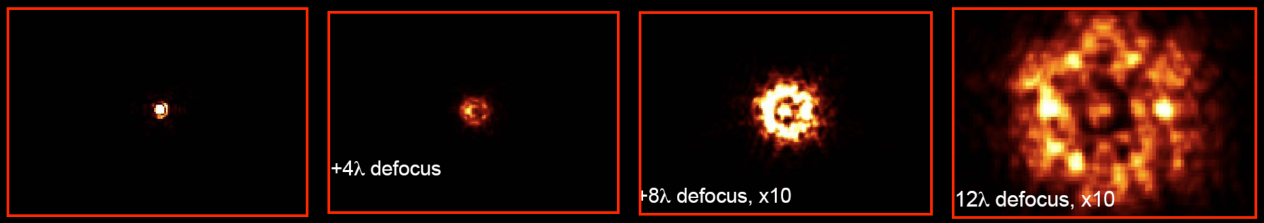
- High contrast imaging and spectroscopy of Brown Dwarfs and Extrasolar Giant Planets
- Formation of planetary systems: tracing evolution of planetary systems from dust clouds to debris disks
- Studies of water and prebiotic organics in comets;
- Characterize organic and inorganic matter needed to create habitable environments
- Characterization of exoplanets via transit imaging

Transit Science Instrument Modes

SI	λ (µm)	Spectral Resolution (λ/δλ)	FOV	Mode	Comments	Application
NIRCam	0.6 - 2.3 2.4 - 5.0	4, 10, 100 4, 10, 100	2 x (2.2' x 2.2') 2 x (2.2' x 2.2')	Imaging Imaging	Photometric Imaging	High precision light curves of transits from photometry of point source images. Wavelength coverage permits photometric monitoring of primary or secondary eclipses.
NIRCam	0.6 – 2.3	4, 10, 100	2 x (2.2' x 2.2')	Phase diversity imaging	Defocusing of images to 57 or 114 pixel diameters	High precision light curves of transits associated with bright objects which need to be defocused to avoid saturation within the minimum integration time
NIRCam	2.4 – 5.0	2000	2 x (2.2' x 2.2')	Long-λ Grism	Backup capability for WFSC. Used with F277W, F322W, F356W, F410M or F444W	Emission spectroscopy of hot gas giant transiting planets
NIRSpec	1.0 – 5.0	100, 1000, 2700	0.1" x 2.0", 0.2" x 3.5", 0.4"x 4.0"	Spectroscopy	Fixed long slits	Low and intermediate resolution transmission and emission spectroscopy of transiting planets.
NIRSpec	0.7 - 5.0	2700	3" x 3"	Spectroscopy	Integral Field Unit	Intermediate resolution, transmission and emission spectroscopy of transiting planets.
MIRI	5 – 29	4-6	1.9' x 1.4'	Imaging	Photometric Imaging	
MIRI	5 - 11	100	5" x 0.2"	Spectroscopy	Fixed Slit or Slitless	Light curves of transits from photometry of point source images.
MIRI	5.9 – 7.7 7.4 – 11.8 11.4 – 18.2 17.5 – 28.8	3000 3000 3000 3000	3.7" x 3.7" 4.7" x 4.5" 6.2"x 6.1" 7.1"x7.7"	Spectroscopy	Integral field unit	Intermediate resolution, emission spectroscopy of transiting planets.
TFI	1.6 – 2.5	100	2.2' x 2.2'	Imaging	Selectable central λ	High precision light curves of transits from photometry of point source images. Wavelength coverage permits photometric monitoring of primary eclipses.
TFI	3.2 – 4.9	100	2.2' x 2.2'	Imaging	Selectable central λ	High precision light curves of transits from photometry of point source images. Wavelength coverage permits photometric monitoring of secondary eclipses.

NIRCam Team Transit Science

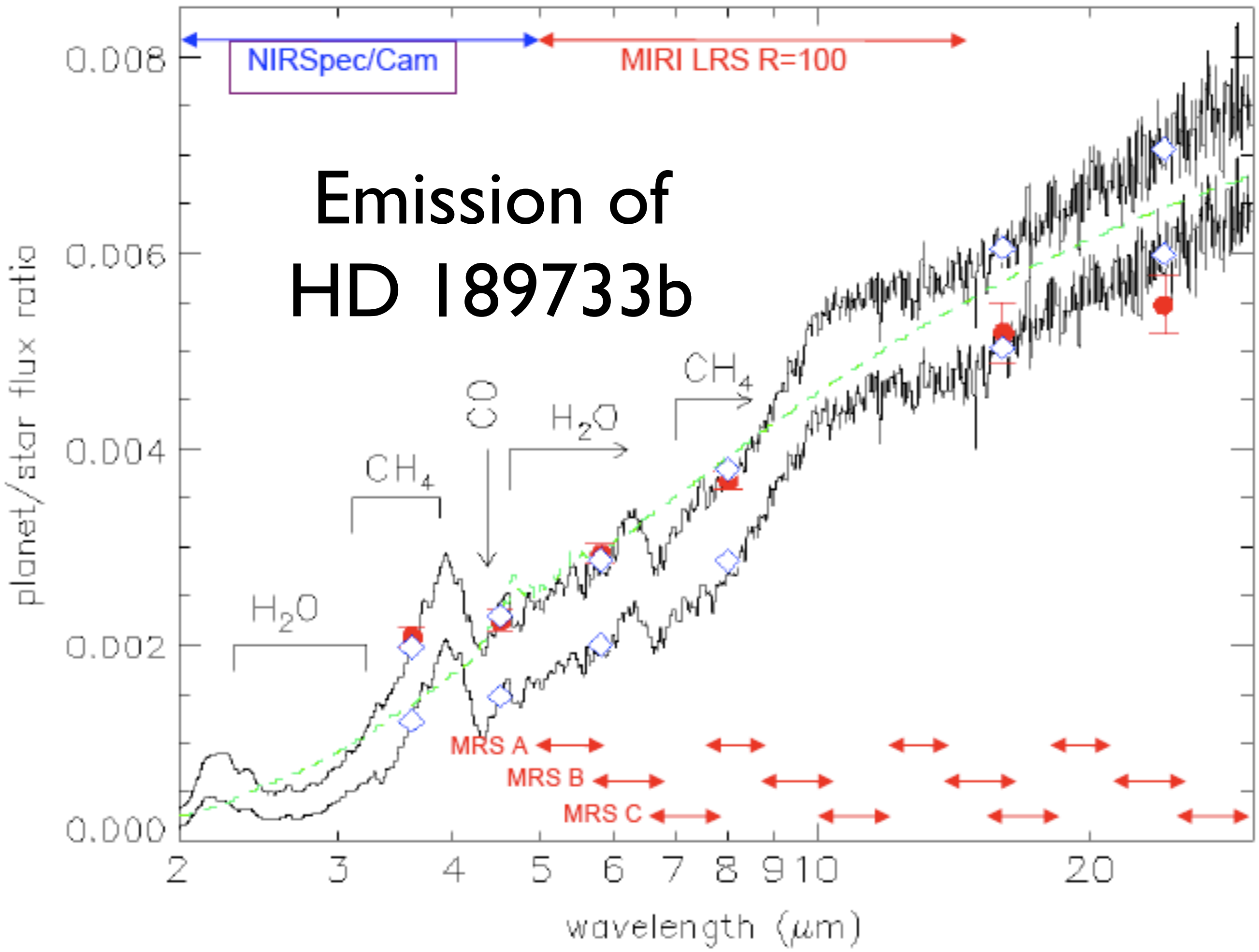
- R~1700 over entire LW channel, λ = 3 - 5 μm simultaneously (but limited by filters in series)
- No slit losses w/good sampling (0.065” vs NIRSpec 0.1”)
  - Precise transit spectrophotometry
  - Especially important for eclipse mapping
- Defocused imaging for transit photometry
  - Sub-arrays available for defocused imaging
  - 4λ, 8λ, 12λ waves of defocus



NIRCam Performance

- Secondary eclipses of a hot Jupiter around bright G2V stars realistic to detect in R≤500 spectra.
- Hot Earths cannot be detected around G2V stars in R=500 secondary eclipse spectra
- High S/N R=500 spectra of a Jupiter around M2-3V stars can be observed via secondary eclipse.
- Secondary transits of Hot Earths around M5V stars could be detected at low SNR in R~50 spectra in ~10^4 sec

NIRCam ➠ MIRI



CH4, CO, H2O constrain temperature and C abundance

Red symbols are measurements;

Top curve has fluz absorbed on day side only; bottom has uniform energy redistribution

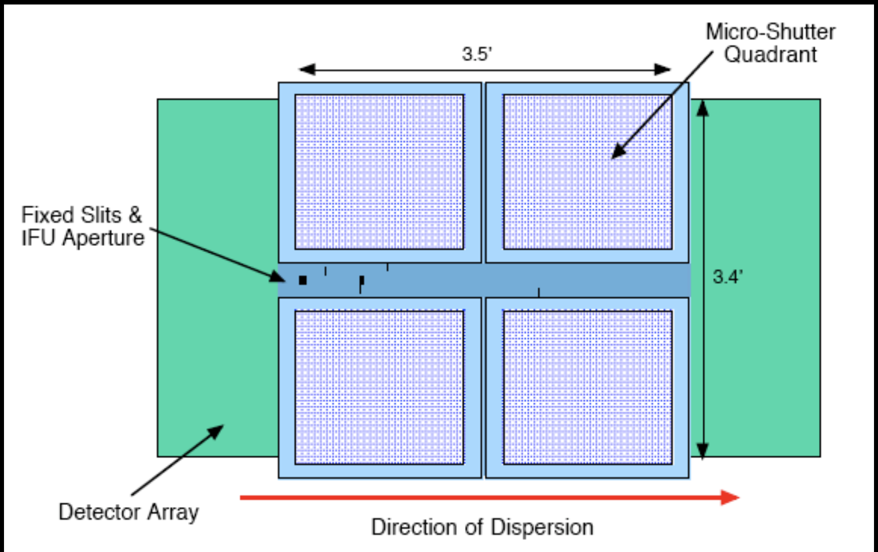
Dashed line is BB

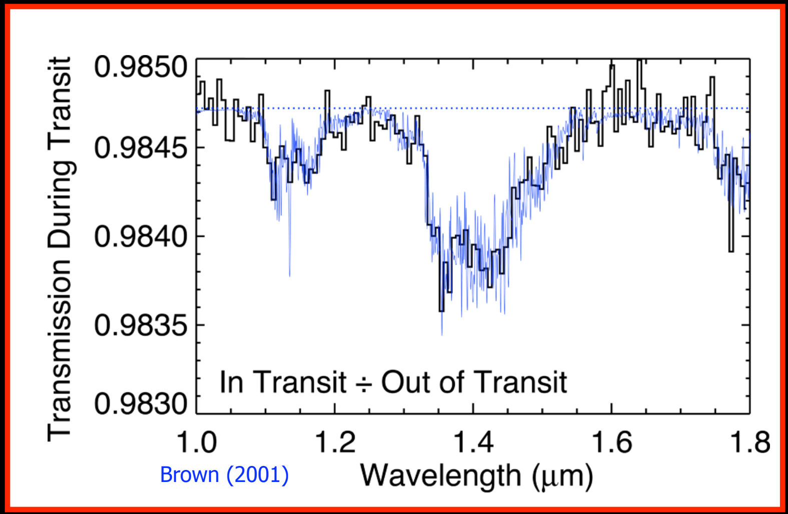
Charbonneau, Knutson, Barman, Allen, Mayor, Megeath, Queloz, & Udry (2008)

MIRI Team Science

- Imager can observe bright sources with good sampling
- MIRI imager should detect even small (1-2 $R_{\oplus}$) planets when transiting bright GKM stars
- LRS may be best to characterize the spectra of hot giant planets with high S/N and at R<=100 spectral resolution
  - Hot giant features detectable in a single transit @ R~50!
- MRS will be useful for R = 100 – 2000 spectra
  - 3 settings required to cover any broad spectral range

NIRSpec Team Science



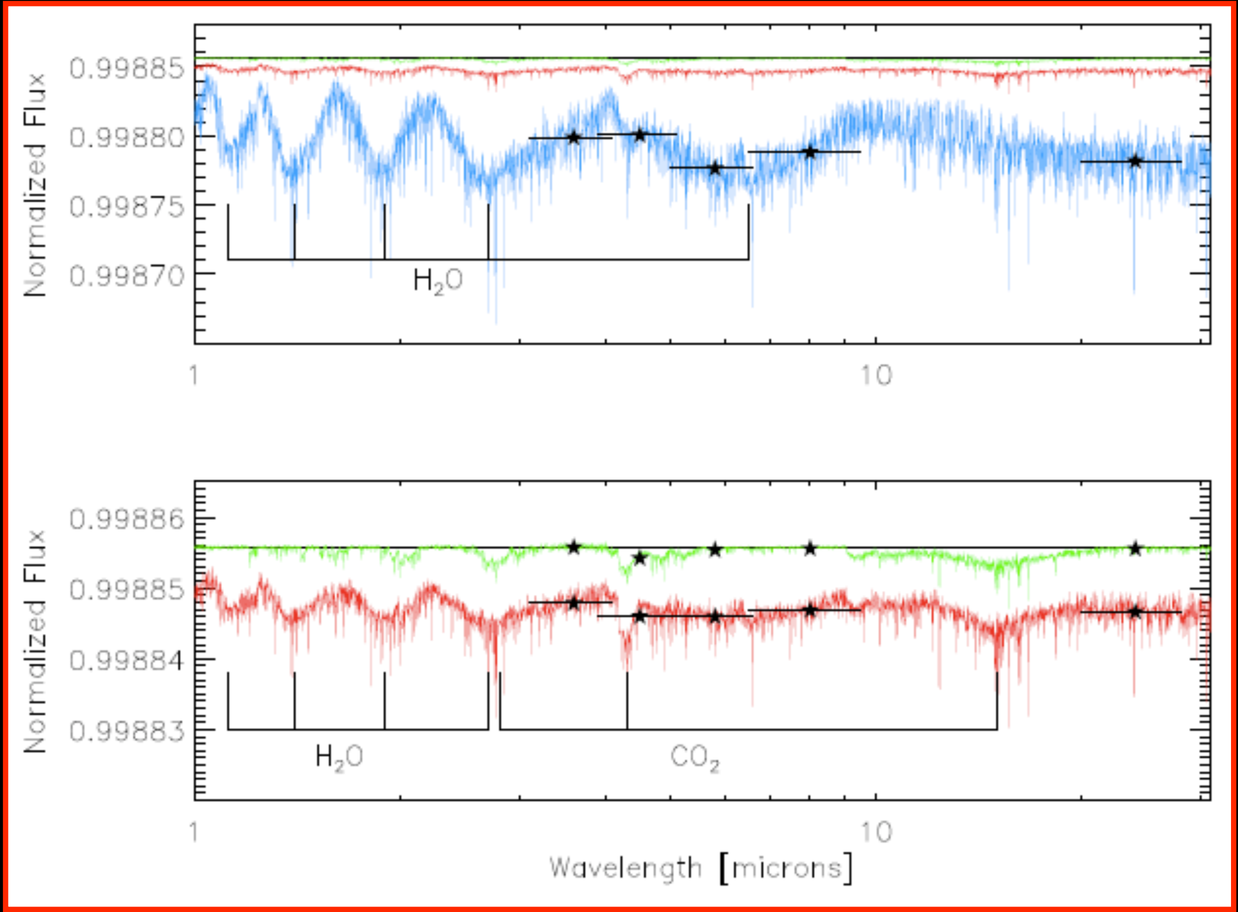


NIRSpec Transit Spectrum for HD 209458 at K=12

- NIRSpec designed for multi-object
- Recently added 1.6’x1.6” slit for transit spectroscopy
- Undersampled pixels remain a concern wrt systematics

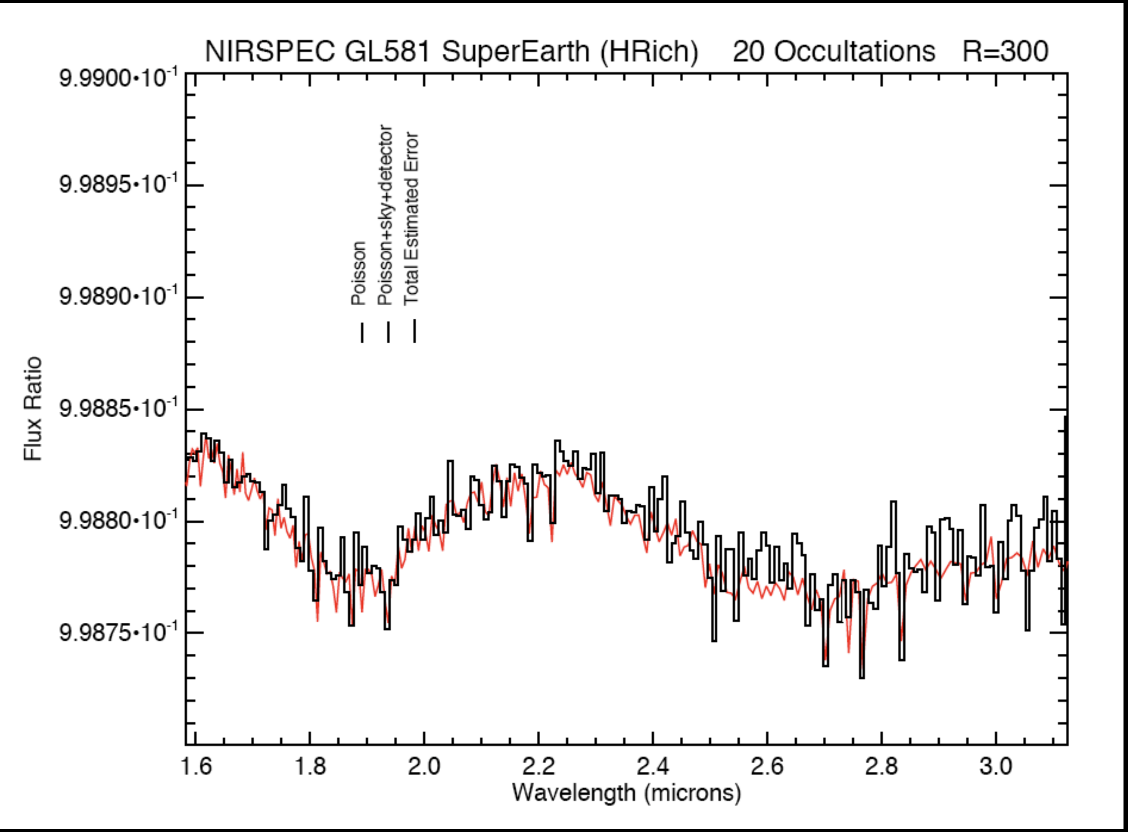
Model Spectra

- **The Atmospheric Signatures of Super-Earths: How to Distinguish Between Hydrogen-Rich and Hydrogen-Poor Atmospheres,** **Eliza Miller-Ricci, Sara Seager & Dimitar Sasselov,** [2008arXiv0808.1902M]



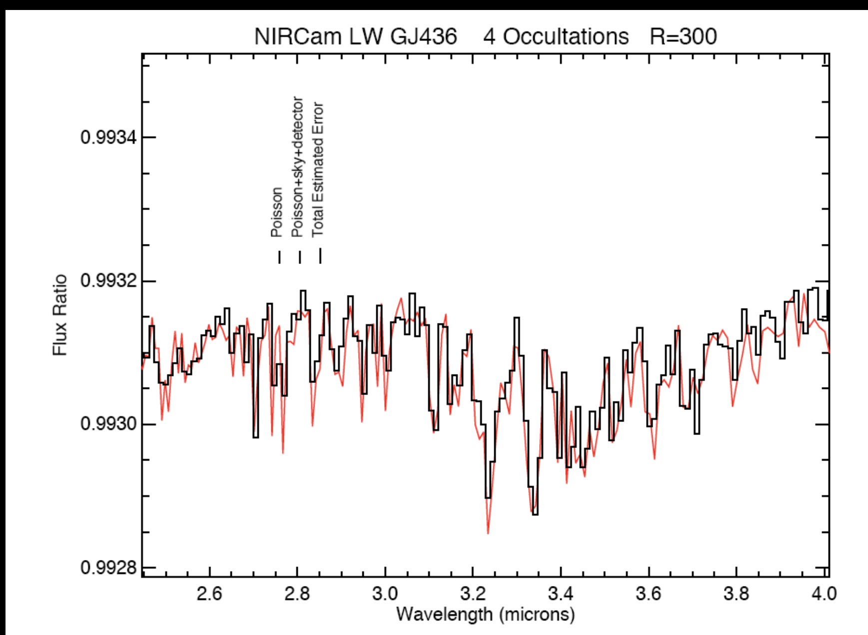
GL 581 - H$_{rich}$ Superearth

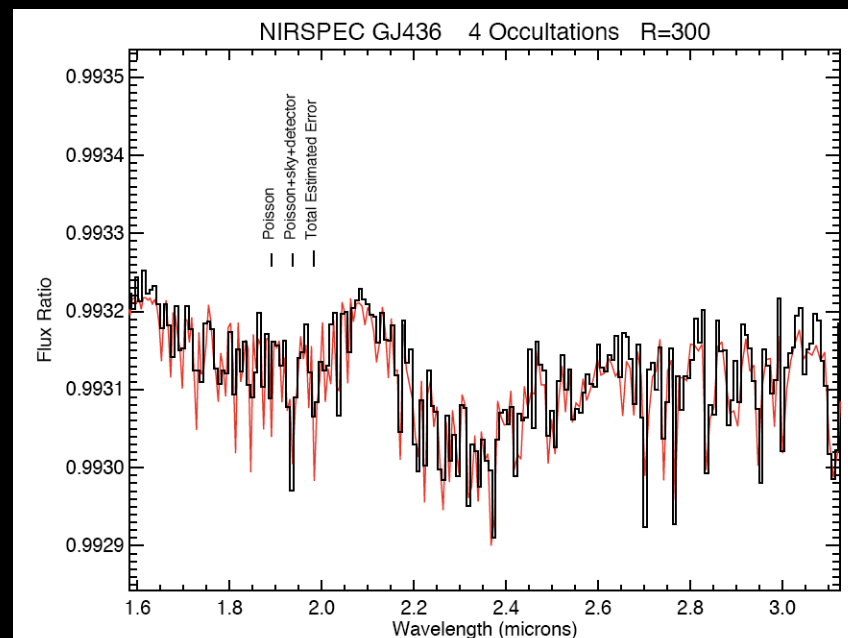
- NIRSpec - 20 transits
- Binned to R~300



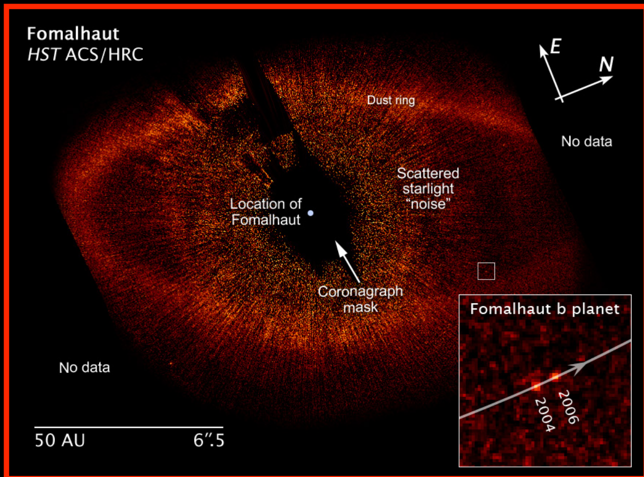
GJ436 _ Transmission

- **NIRSpec - 4 transits**
- **Binned to R~300**

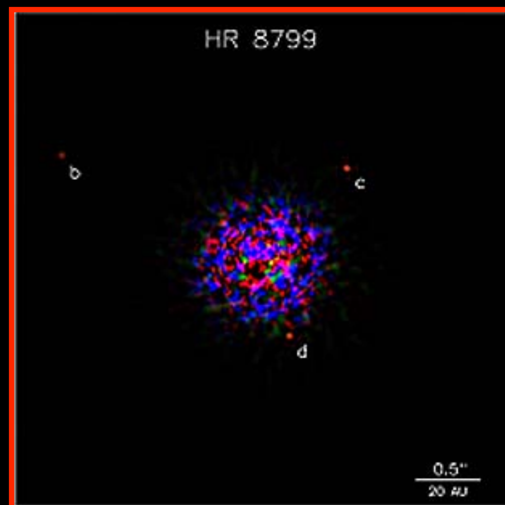




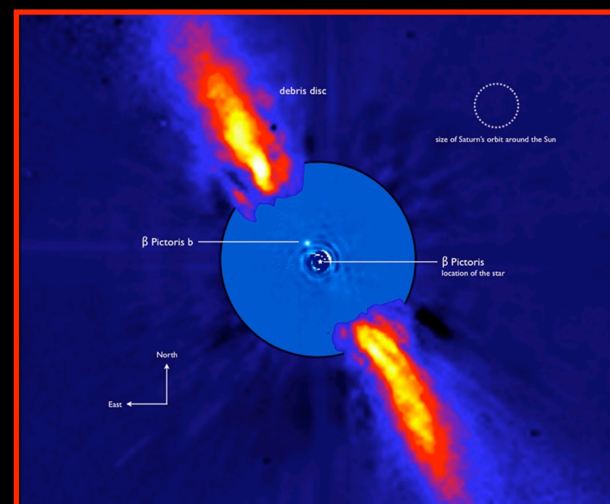
Crop of Recent Detections!



Fomalhaut B
Kalas et al. 2008



HR 8799
Marois et al. 2008



β Pictoris
A. M. lagrange et al. 2009

Imaging/Spectroscopy Modes

Instrument	Channel/Mode	λ (μm)	R (λ/δλ)
NIRCam	Short λ Lyot Coronagraph	0.6 - 2.3	4, 10, 100
NIRCam	Long λ Lyot Corongagraph	2.4 - 5.0	4, 10, 100
TFI	Multi-λ coronagraph	1.6 - 2.5	100
TFI	Multi-λ coronagraph	3.2 - 4.9	100
TFI	Non-redundant mask	1.6 - 2.5	100
TFI	Non-redundant mask	3.2 - 4.9	100
MIRI	Quadrant Phase Coronagraph	10.65	20
MIRI	Quadrant Phase Coronagraph	11.4	20
MIRI	Quadrant Phase Coronagraph	15.5	20
MIRI	Lyot Coronagraph	23	5

High Contrast Imaging

MIRI	Integral field spectrograph	5.86 - 7.74	3000
MIRI	Integral field spectrograph	7.43 - 11.84	3000
MIRI	Integral field spectrograph	11.44 - 18.20	3000
MIRI	Integral field spectrograph	17.53 - 28.75	2250
NIRSpec	Integral field spectrograph	0.7 - 5.0	2700

Integral Field Spectroscopy

Coronography (Dressler summary)

- NIRCam coronagraph (Krist 2007; Greene et al 2006)
  - Inner Working angle $\geq 4\lambda/D$ (500-750 mas at 3-5 μm)
  - Outer Working Angle ±10”
  - Dynamic range 10^5 (12.5mag) - 10^6 (15 mag) far from star
- TFI/Non Redundant Mask (Sivaramakrishnan et al)

– Inner Working angle ~ $0.5\lambda/D$ (75 mas at 5 μm)

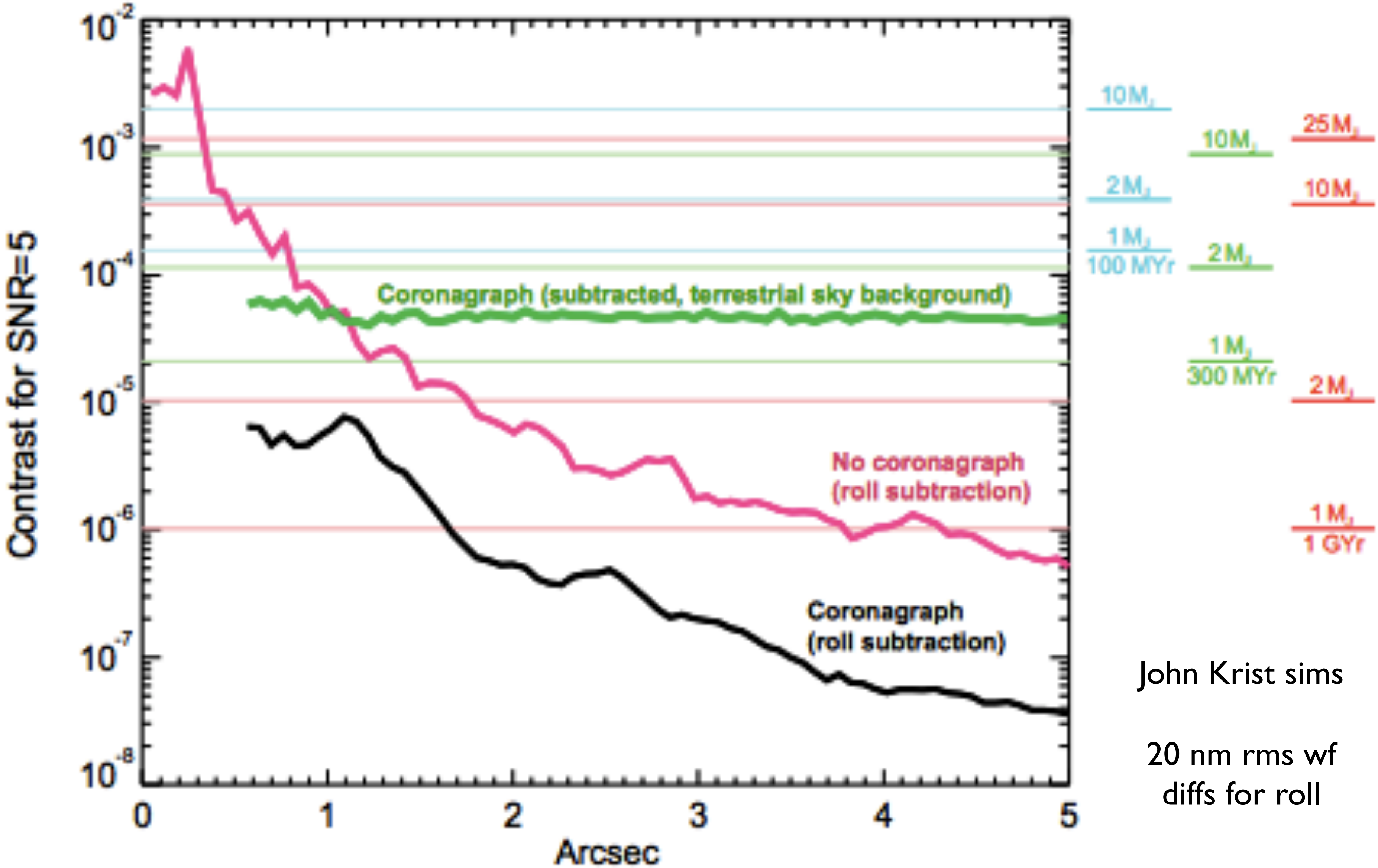
– Outer Working Angle 0.5”

– Dynamic range 10^4 (10 mag) possibly up to 10^6 (12.5 mag) with careful calibration, flat fielding

- MIRI classic Lyot and 4-quadrant phase plate

– Mostly disks but also planets on distant orbits (Fomalhaut-b)

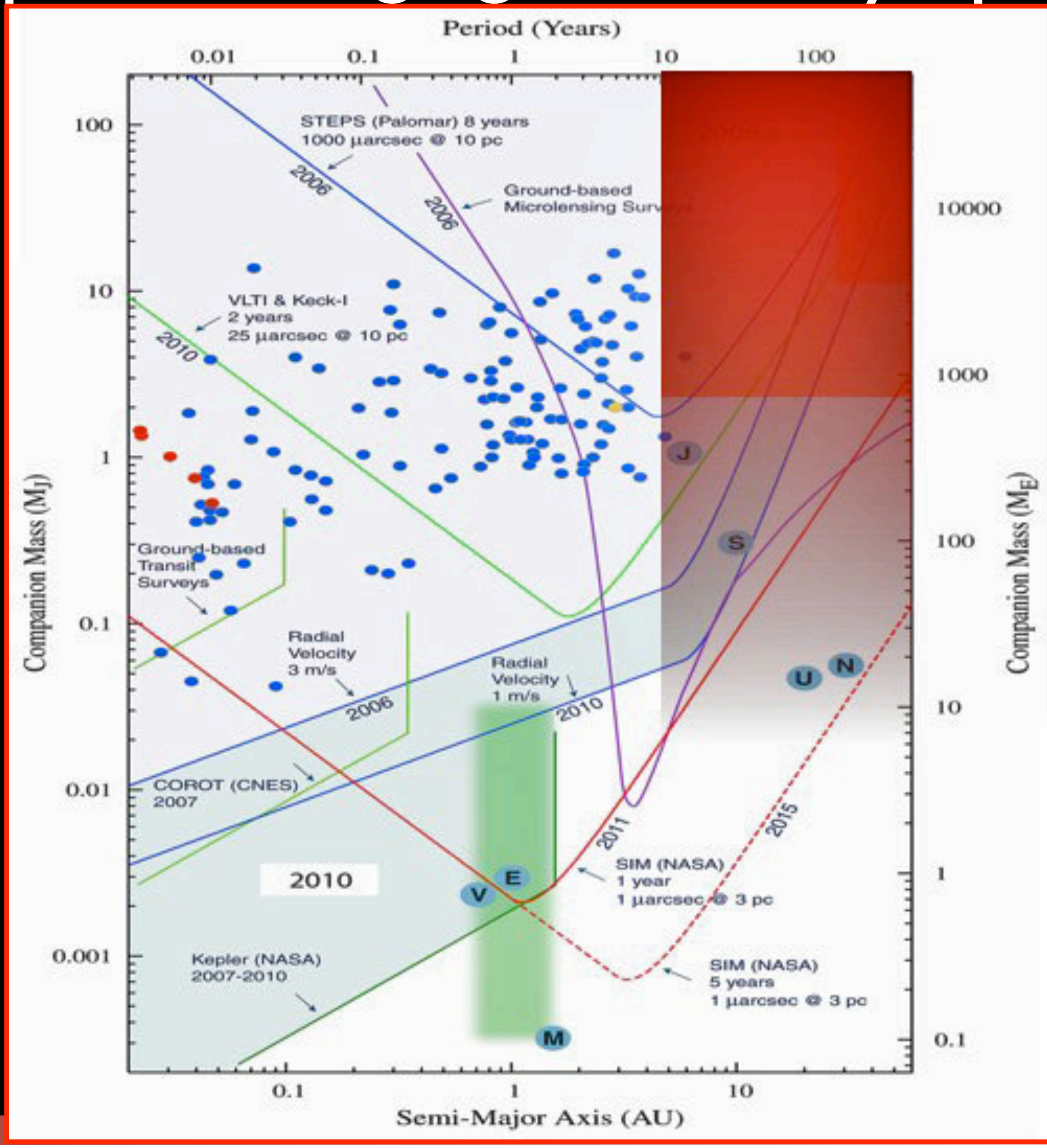
NIRCam: M0V Star at 4 pc (F460M)



John Krist sims

20 nm rms wf diffs for roll

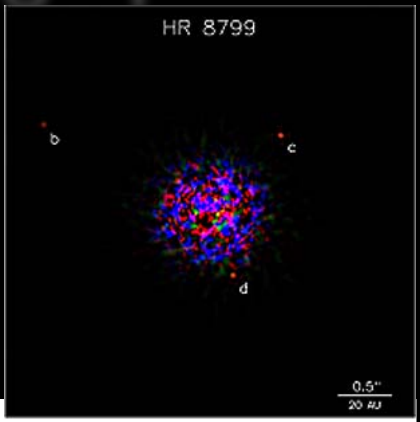
Exoplanet Imaging Discovery Space

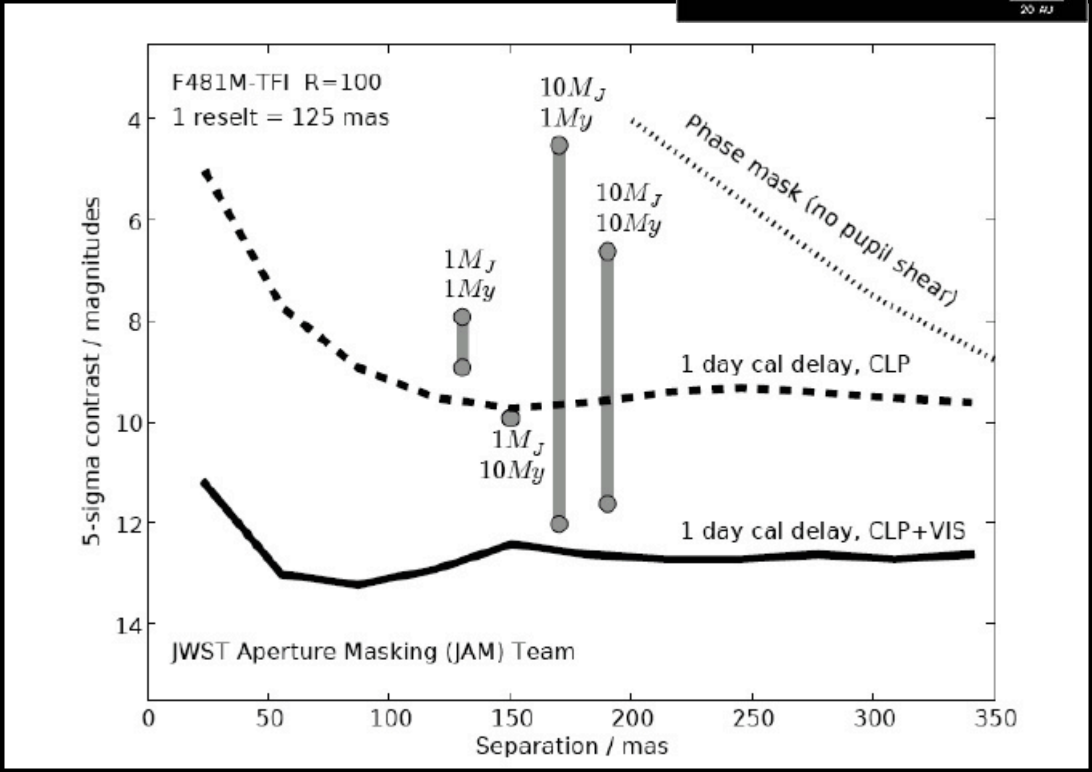


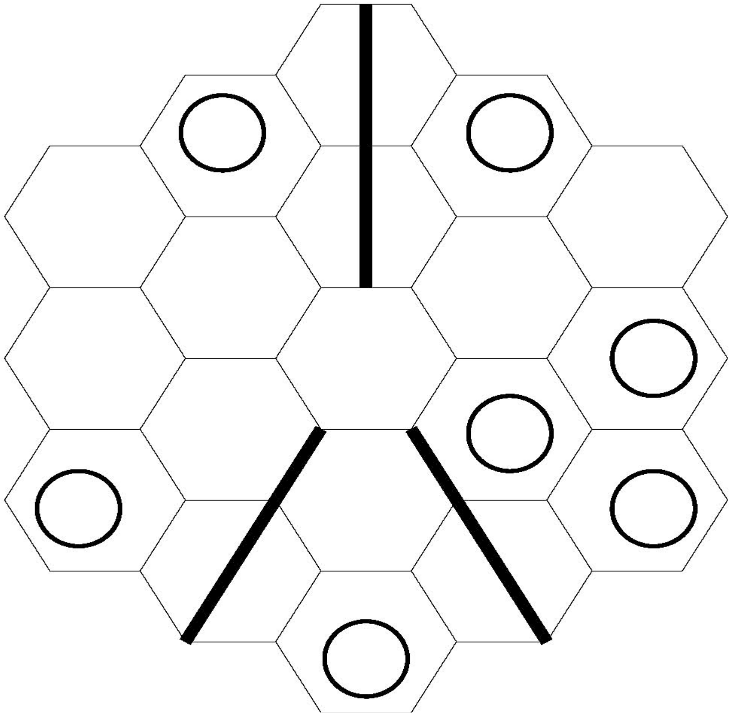
Courtesy M. Meyer

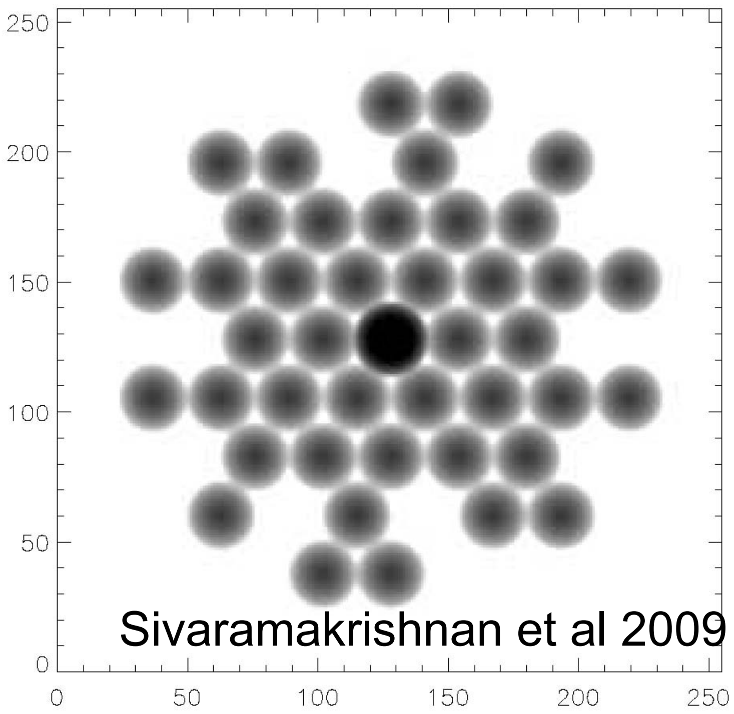
Tunable Filter Imager Coronagraph

- **TFI Coronagraphic Capability Summary**
  - **Wavelength range:** 1.5-2.5, 3.1-5.0 μm
  - **Field of view:** 20″x20″
  - **Coronagraph**: Differential Speckle Imaging
  - **Contrast** gain of ~10x versus NIRCam
  - **Inner working angle: 4 λ/D**
  - Technique employed on HR8799 (Marois et al. 2008)
- **Non-redundant Mask**
  - **Wavelength range:** 1.5-2.5, 3.1-5.0 μm
  - **Coronagraph**: Closure Phase Imaging
  - **Trades inner working angle: 0.5 λ/D against contrast**





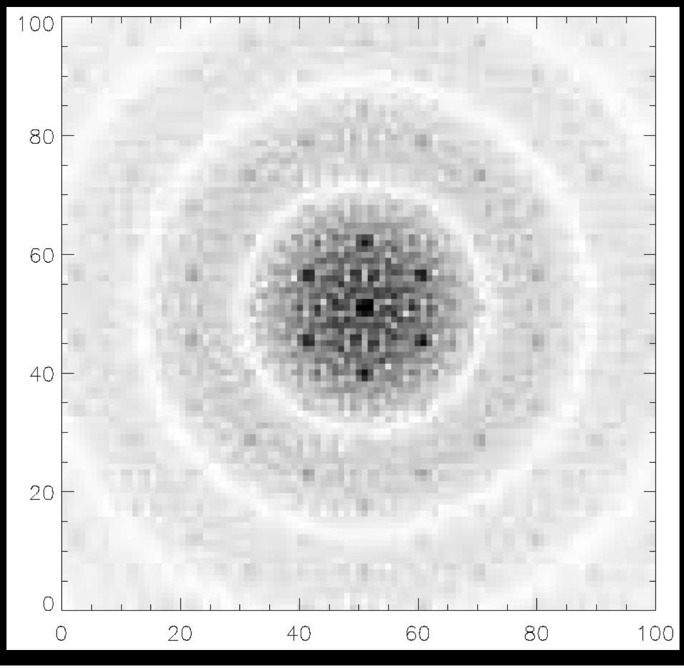




Sivaramakrishnan et al 2009

Non-Redundant Mask Imaging

- New mode for FGS/TFI utilizes "interferometric" mask producing 21 baselines and a narrow PSF (0.5λ/D)
- Ground-based contrast limits ~5 mag, in space > 10 mag possible at small IWA
- Flat fielding issues may be problem (>>Photon noise) for bright stars



Performance of the Non-redundant phase mask

Table 1 – Log_{10} of planet/star contrast at 4.6 μm (TFI Coronagraph)[1]

Sp	M_m	0.01 Gyrs			0.10 Gyrs			1 Gyrs			5 Gyrs		
		1 M_J	5 M_J	10 M_J	1 M_J	5 M_J	10 M_J	1 M_J	5 M_J	10 M_J	1 M_J	5 M_J	10 M_J
A0	0.78	-5.09	-4.16	-3.78	-5.96	-4.94	-4.47	-7.67	-5.83	-5.33	-8.87	-6.95	-5.97
F0	2.27	-4.49	-3.56	-3.18	-5.37	-4.35	-3.88	-7.07	-5.24	-4.74	-8.27	-6.36	-5.38
G2	3.58	-3.97	-3.04	-2.66	-4.84	-3.82	-3.35	-6.55	-4.71	-4.21	-7.75	-5.83	-4.85
K0	4.29	-3.68	-2.76	-2.38	-4.56	-3.54	-3.07	-6.26	-4.43	-3.93	-7.46	-5.55	-4.59
K5	4.69	-3.52	-2.60	-2.22	-4.40	-3.38	-2.91	-6.10	-4.27	-3.77	-7.30	-5.39	-4.41
M0	5.15	-3.34	-2.41	-2.03	-4.22	-3.20	-2.72	-5.92	-4.08	-3.58	-7.12	-5.20	-4.22
M5	7.98	-2.21	-1.28	-0.9	-3.08	-2.06	-1.59	-4.79	-2.95	-2.45	-5.99	-4.07	-3.09
L0	10.15	-1.34	-0.41	-0.03	-2.22	-1.20	-0.72	-3.92	-2.08	-1.58	-5.12	-3.22	-2.22
L5	10.98	-1.01	-0.08	0.30	-1.88	-0.86	-0.39	-3.59	-1.75	-1.25	-4.79	-2.88	-1.89
T0	11.40	-0.84	0.09	0.48	-1.72	-0.70	-0.22	-3.42	-1.58	-1.08	-4.62	-2.70	-1.72
T5	12.38	-0.45	0.48	0.86	-1.33	-0.31	0.16	-3.03	-1.20	-0.70	-4.23	-2.31	-1.34

Contrast exceeds the 10σ sensitivity beyond 1". [2]

Contrast exceeds the 10σ sensitivity beyond 5". [2]

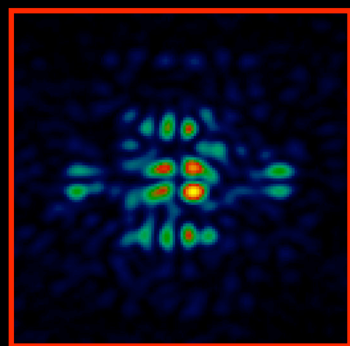
Contrast exceeds the 10σ sensitivity beyond 1" *without* coronagraph and no PSF calibration.

[1] Evolutionary models from Barraffe *et al* 2003.

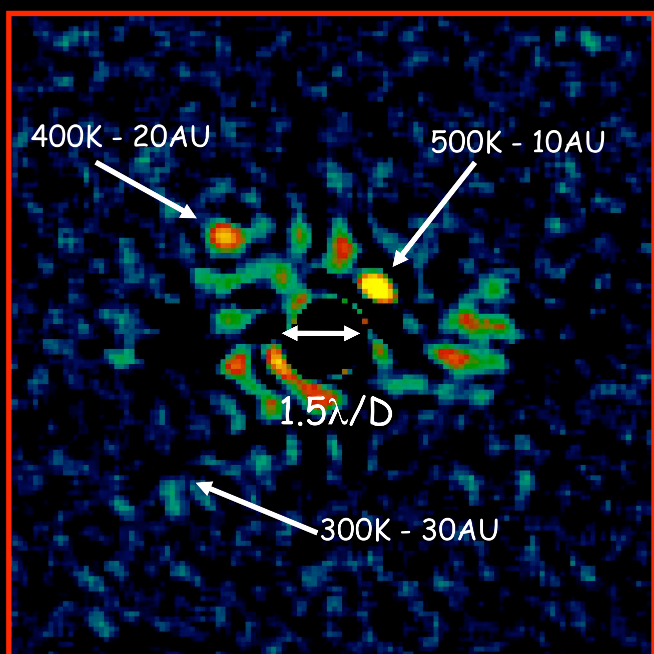
[2] Contrast threshold assuming the 2" (FWHM) occulting spot and a speckle noise attenuation factor ~10x

MIRI Exoplanet Detection Limits

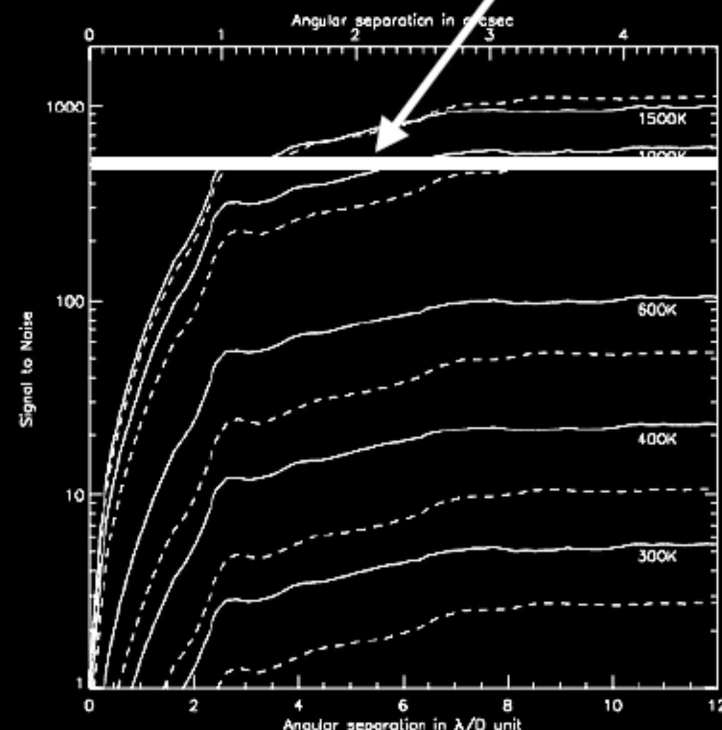
Boccaletti et al.



M2V, 10pc

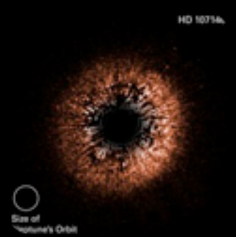


Detection limit (5-σ) with
30-m groundbased telescope

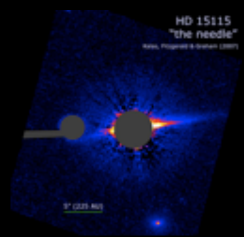


Signal to noise ratio of EGPs at 11μm as a function of the radial separation assuming a system located at 10 pc around an M2V star. The dotted and solid lines correspond respectively to the signal to noise ratio in the first and the second filters (ammonia absorption)

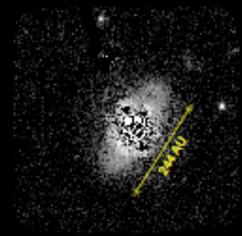
Debris Disks: HST's Legacy



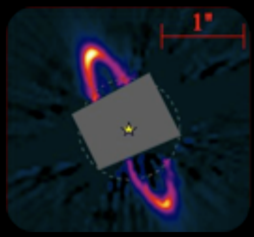
HD 107146
Ardila et al. 2005



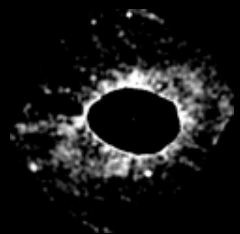
HD 15115
Kalas et al. 2005



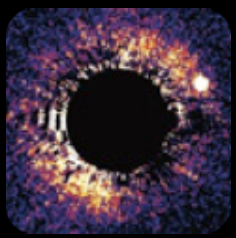
HD 92945
Clampin et al. 2006



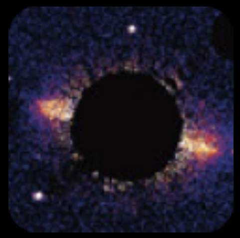
HR 4796
Schneider et al. 1999



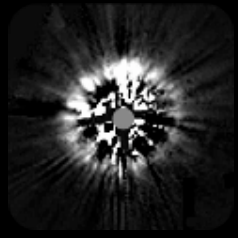
HD 207129
Stapelfeldt et al. 2007



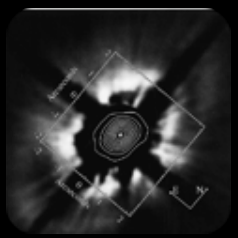
HD 139644
Kalas et al. 2006



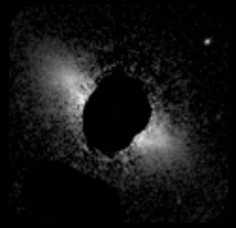
HD 51543
Kalas et al. 2006



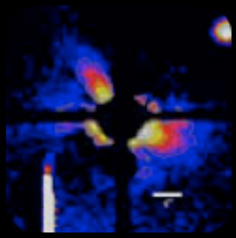
HD 181327
Schneider et al. 2006



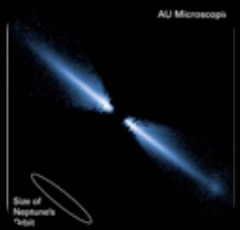
HD 141569A
Weinberger et al. 1999



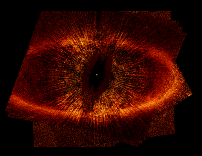
HD 10647
Stapelfeldt et al. 2007



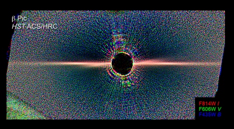
HD 32297
Schneider et al. 2006



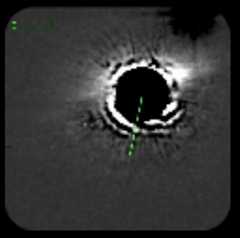
AU Mic
Krist et al. 2005



Fomalhaut
Kalas et al. 2005



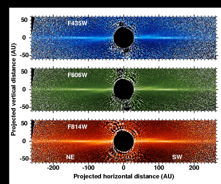
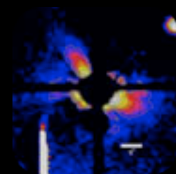
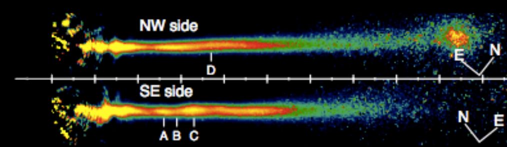
β Pictoris
Golimowski et al. 2005



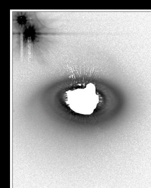
HD 202917
Clampin et al. 2007

Debris Disks: Evidence for Planets

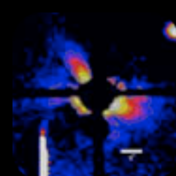
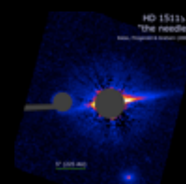
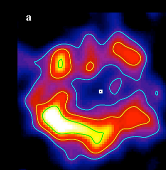
- **Warps**

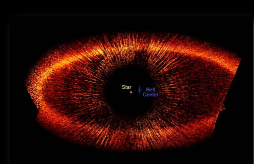
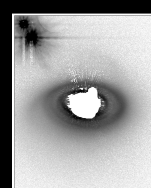
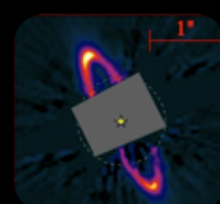
- **Spirals**



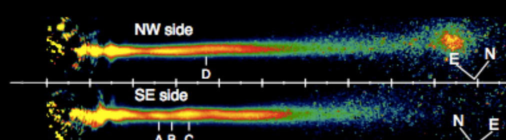
- **Brightness Asymmetries**

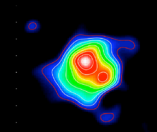
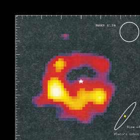
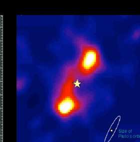
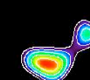




- **Offsets**

- **Clumps**

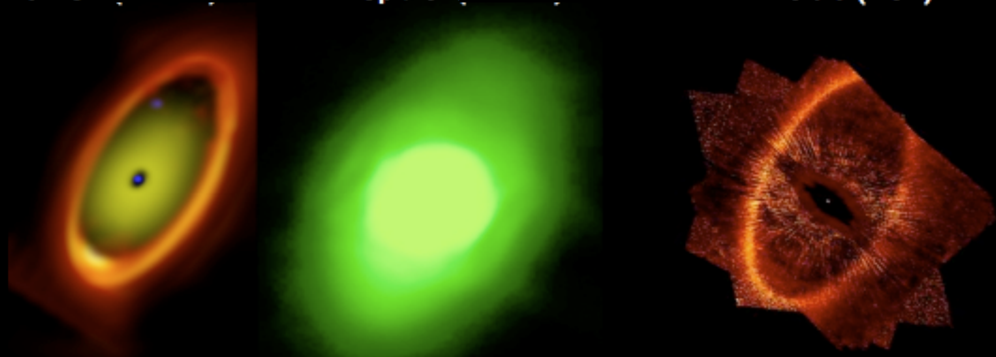


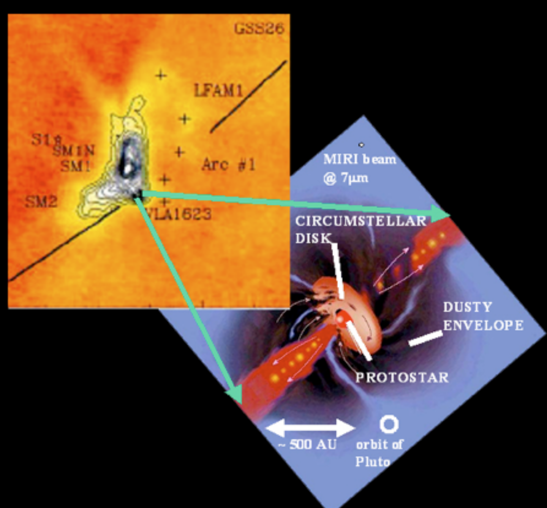
MIRI: Disk Characterization

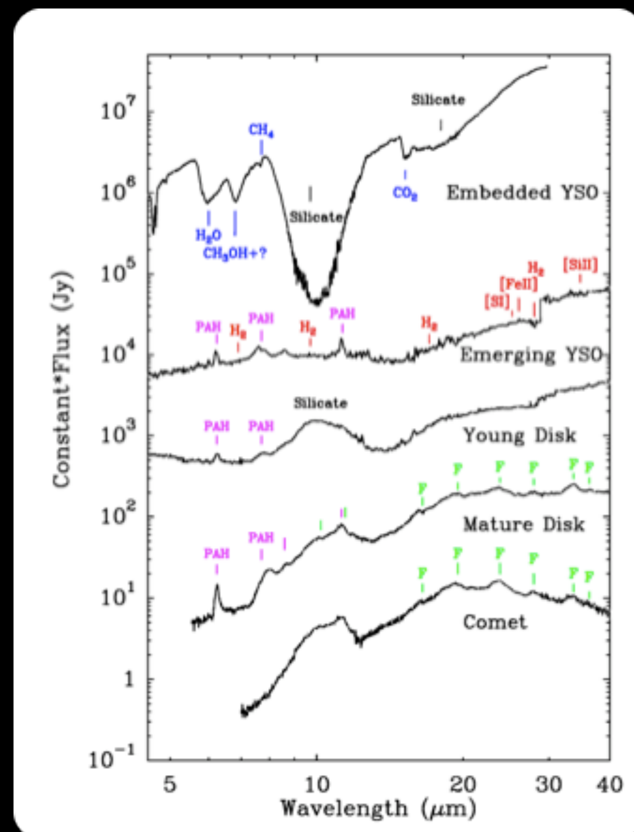
- Disk morphology: scattered light & emission
- Disk minerology

JWST 20 microns
Spitzer 24 microns
Visible (HST)



Fomalhaut





Summary

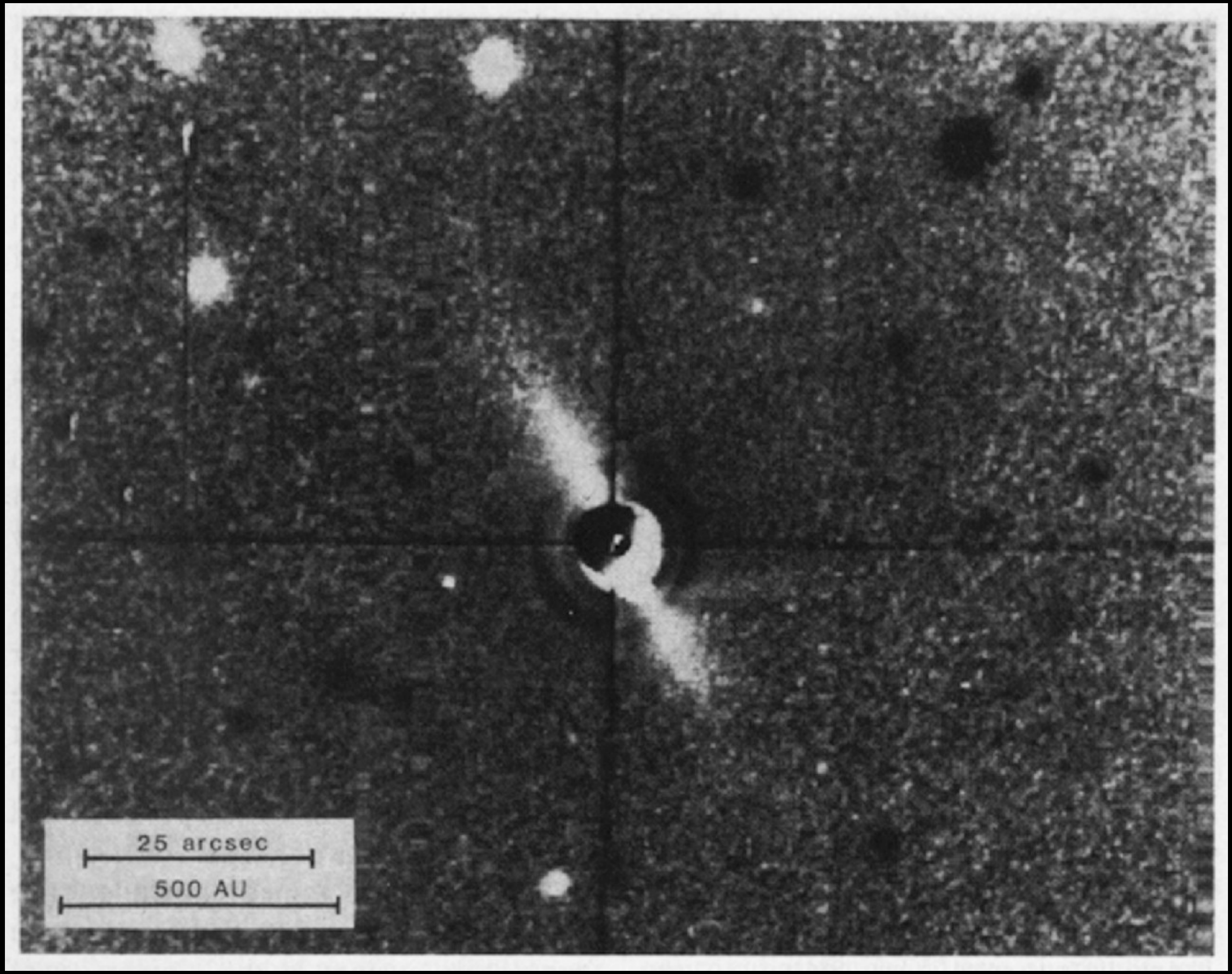
- JWST is on track for 2013 launch – a major accomplishment!
- Predicted performance for exoplanet transits is very good (limited by systematic errors and unknown stability)
- 3 coronagraphs provided but segmented aperture not optimal
- Small changes made for better photometric stability (NIRSpec) and better inner working angle (TFI non-redundant mask)

The End

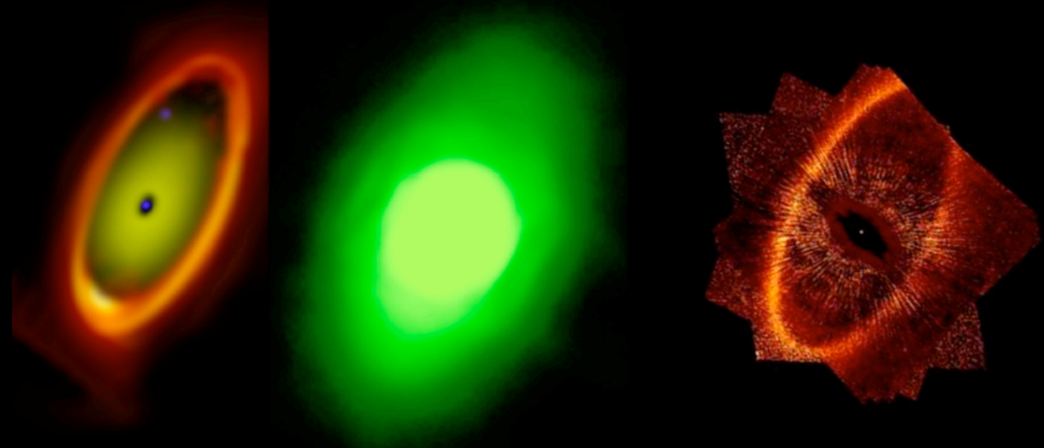
Pluto?


I CAN'T BELIEVE
I HAVE TO SIT AT THE
"LITTLE PLANETS"
TABLE...
PLUTO

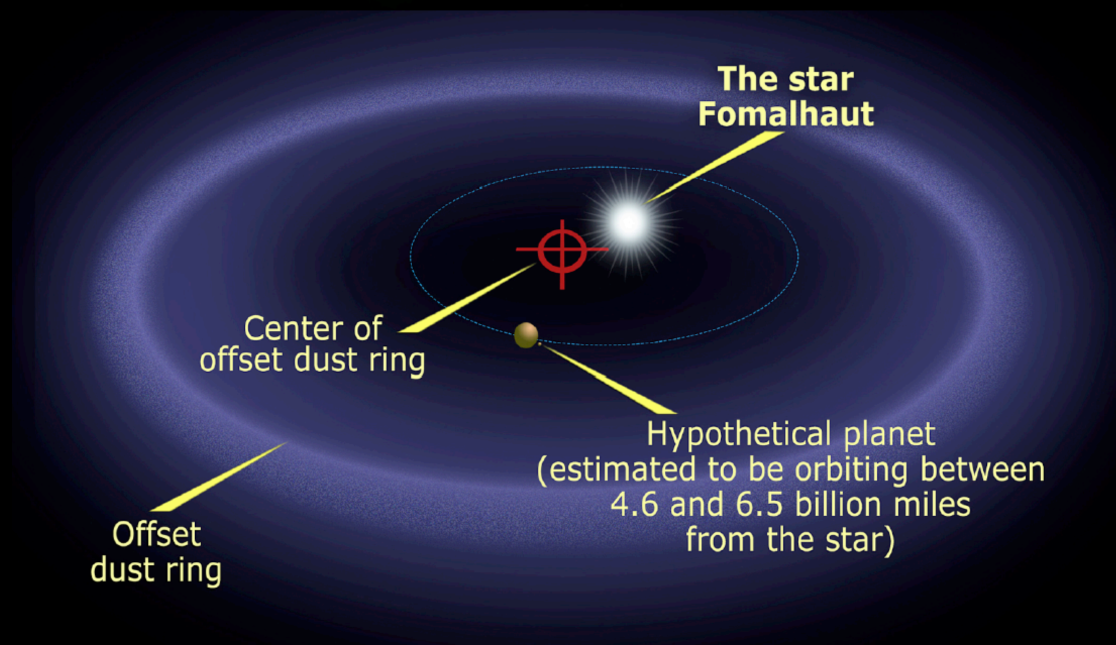
Debris Disks: β Pictoris



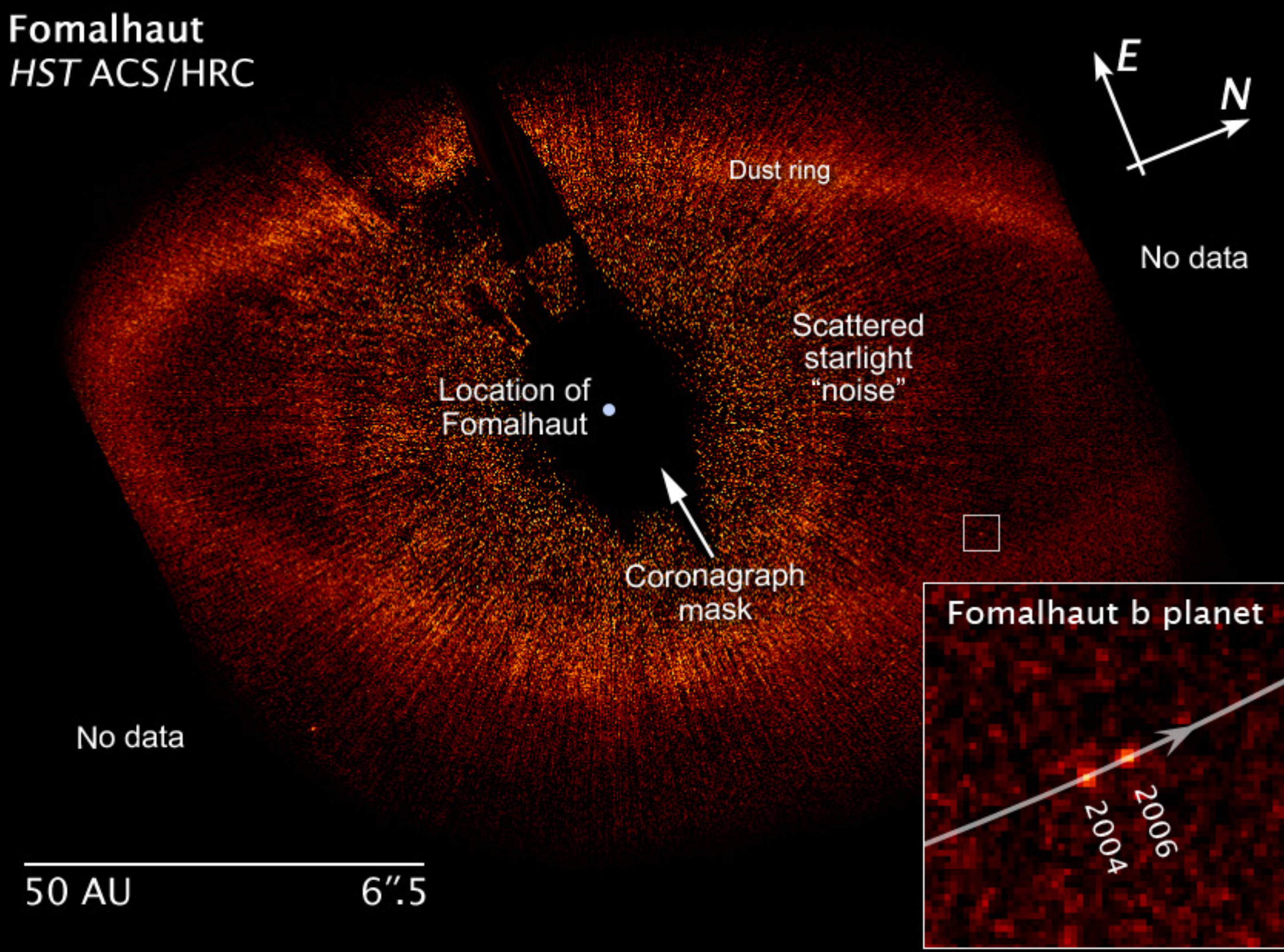
JWST Observations of Fomalhaut



Fomalhaut



Direct Detection



- Mark McCaughrean, a JWST SWG member and astrophysicist at the University of Exeter quoted by BBC
- "It's like a London bus - you've been waiting for one for ages and suddenly four come along at once."

- and more to come!

Flight Mirror A1